THE

SCIENTIFIC PRINCIPLES OF GRAIN STORAGE

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PREFACE

It appears that there has not been, up to the present, any work in the English language devoted specially to the problems involved in the storage of grain. The only other works in any language of which I am aware are "Das Getreidekorn" by Hoffmann and Mohs, and "I Depositi di Cereali" by A. Luraschi, the former being in German (and long out of print) and the latter in Italian. The present book differs from both of the foregoing in that it deals somewhat more comprehensively with the scientific principles of grain storage but not at all with the design of storage structures. It is not, therefore, a text book on the design of storage places but will, I hope, provide a useful background for architects and engineers who are concerned with buildings and machinery for the grain industry. Also, I have taken the opportunity in this book of bringing together a good deal of information which will be of value to all who handle or use grain whether or not they are concerned with storage.

I believe that there has long been need for a book dealing with this subject, not only to dispel the many false impressions which I have found to be common among my friends in agriculture and the grain trade, but also to provide a summary of present knowledge which can act as a starting point for future research. In my view such research ought now to be put in hand if there is to be a proper scientific foundation for future developments in grain storage. I have therefore attempted to cater for both the scientist and the non-scientist, each of whom will, I hope, find something of value to him which would be difficult to find elsewhere.

I am glad to acknowledge the help and advice of my colleagues at the Pest Infestation Laboratory, particularly Mr. M. E. Solomon, who gave valuable information on the biology of mites and read and criticized Chapter 13, and Mr. R. W. Howe, who advised on the chapters dealing with the biology of grain insects.

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CHAPTER 1

THE HAZARDS OF GRAIN STORAGE

All kinds of cereal grains are relatively easy to store. Their value as a food for mankind rests quite largely on their permanence in storage, and it is safe to say that the successful development of agriculture by man, and hence the evolution of civilization, would have been impossible if crops of the durability of dry cereal grains had not existed.

The cradle of civilization was in a relatively dry part of the world. The chief significance of this may lie in the fact that cereal grains are easy to store only if they are dry at the time of harvest. In damper climates it has only been possible to develop cereal cultivation successfully by means of methods of harvest (e.g. stooking and stacking) which enable the grain to dry after cutting and prevent accumulation of heat. The modern problem in damp temperate climates such as that of Western Europe is set by the introduction of combine harvesting which was developed in dry parts of the world but is now spreading to countries to whose climate it is not basically suited. There is no need to complain at or regret the spread of combine harvesters into the damper countries, the saving in man-power which they effect is of the utmost value, but the storage difficulties which they bring must be fairly recognized and properly studied.

Great Britain largely depends on imported cereals and, since these are supplied by countries basically suited to grain production, they are usually dry when received in this country and the worst hazards of grain storage are avoided. In fact we are provided with grain in the stable condition in which it was available to our earliest ancestors when they first found that it could be stored from season to season without difficulty. Nevertheless, it is a mistake to suppose that all imported grain may be regarded as a perfectly stable material which may be treated like sand or bricks and left without any attention in any sort of storage. The hazards of storage are certainly much less for dry grain than for damp grain but they nevertheless exist.

At the present time, with a world shortage of all cereals, there will be very little prolonged storage, and the driest grain is unlikely to give any trouble, but the need to produce the utmost which world agriculture is capable of must result in a large production of damp, potentially hazardous, grain. Nothing must be wasted and it is most important that we study the causes of grain deterioration in storage. Damp grain will force its instability on our notice whether we like it or not ; dry grain may be safe at the moment but our study of storage methods for this material must be continued in preparation for the time when it is again necessary to hold large quantities in store for considerable periods.

World management of grain supplies is certainly the next development for the future. It will aim at smoothing out fluctuation in supplies from season to season by carrying vast stocks over periods of several years. For the importing countries a return to pre-war conditions of grain supply, with a continuous flow from all parts of the world, is not likely, and probably millers and grain-holding organizations will find it necessary to keep larger stocks for longer periods than formerly. It is therefore clear that a full understanding of the principles of grain storage is necessary for millers, for Governments, and for the world.

The Dormant Grain

Cereal grains are seeds, that is, they are the dormant resting stage of the plant which bears them. Though they are alive, and all living things are continually respiring, producing heat, water, and carbon dioxide, they are at a very low ebb. It is the combined effect of their continued life (which enables them to resist decomposition by micro-organisms) and the very low level of that life, which makes cereal grains such pre-eminently stable bodies in store.

Dormancy of seeds, however, is very largely controlled by water content and when an attempt is made to store grain which is insufficiently dry, the effect of insufficient dormancy is at once shown. The mass becomes hot, steams, becomes mouldy, sprouts at the surface, and finally, when the grains are dead, rots. Fungal and bacterial spores are universally present on all grain and in the air; like the grain they are dormant when dry but as they become damp their activity is increased, they germinate and produce the moulds and bacteria which taint and then rot the stored grain.

It must be noted that the word "dormancy" is used above in its general sense meaning a state of sleep. There is also a specialized use of the word referring to the inability of some seeds (e.g. barley) to germinate even when they are completely imbibed with water and provided with all external necessary conditions of germination. *The word is not to be used in this restricted sense in this book without* special explanation being given.

Insects

If good dry grain is stored away from all chance of becoming damp the chief danger which remains is that it will become infested with insects. This is a serious hazard for it is not countered merely by drying the grain (unless it is dried to an absurdly low moisture content) or by ventilating it. An insect infestation which becomes well established will reproduce most of the features of heating, steaming, and sprouting, which are usually associated with storage of damp grain, with the added trouble that a considerable amount of the grain is consumed with a consequent loss in weight. All too often a bulk of grain affected with an insect infestation, producing apparent dampness, is thought to have got damp in transit or in store and the blame is quite incorrectly laid.

A full discussion of insect infestation problems is given in later chapters, but a few general principles can be emphasized here.

1. Insects are never "spontaneously generated," they can only come from eggs laid by their parent insects.
2. Many insects which infest cereals spend part of their life history within the grains and thus cannot be detected by an ordinary inspection.
3. Some kinds of insect infestation develop deep in a bulk of grain where they cannot easily be detected. They may have done considerable damage by the time they come to the surface and are noticed for the first time; very often insects do not come to the surface until they are driven there by the heating which they have themselves caused.
4. In most cool, temperate, countries the same insects do not infest grain in the field and also in storage. English grain fresh from the field may usually be considered to be free from insect infestation though, if it has been standing in the rick for some time, mites (which are not strictly insects) may be brought in on the grain.

The Kinds of Deterioration

Some optimists argue that whatever happens to grain in store, short of actual rotting, it is never seriously damaged. It is perhaps true that many parcels of grain have been sold at a good price after having suffered alarming heating or insect attack, or have been incorporated in small proportions in the grist without serious detriment. This is possible because grain (even including malting barley) is judged almost entirely by eye and, while some forms of damage can usually be detected in this way, many leave no sign.

It is wrong to underrate the damage which can occur in store merely because the proportion of grain so affected is usually small. We must study and understand the hazards so that we shall be in a position to combat them if changes in the world plan of agriculture or of the grain trade make big changes to storage programmes.

The most important changes which take place in grain during storage may be divided into two groups:

1. Gross obvious changes which are apparent when the grain is examined by eye.
   (*a*) Sprouting.
   (*b*) Moulding and rotting.
   (*c*) Insect damage.
2. Concealed changes, chemical and biological.
   (*d*) Loss of germinative power.
   (*e*) Development of acidity.
   (*f*) Gluten deterioration.
   (*g*) Loss of nutritive qualities.

These changes may be considered in the above order.

SPROUTING. A considerable amount of sprouting can occur in store when grain becomes damp, and the damage which results from mobilization of food reserves and over-production of enzymes is very well known. It is not so generally realized that the most usual cause of dampness in grain is not leaky storage but spontaneous heating in storage (see Chapter 7) and can only be avoided by avoiding the conditions which lead to heating.

MOULDING AND ROTTING. These two phenomena are merely stages of the same process since rotting is a consequence of mould and bacterial activity. Serious mould development and rotting of grain very seldom affects any more than a few restricted parts of any bulk of grain in store. Usually it is possible to neglect the direct effects because the occurrence is very localized, i.e. against a damp wall or under a leaky point in a roof and the affected grain can be removed. Local rotting, however, produces a taint which is much more serious because it appears to spread so far through a bulk. For this reason alone it is worth considerable effort to avoid leaks of water in grain stores.

INSECT DAMAGE. Insect damage usually takes the form of hollowing out of grains by insects whose larvae live inside the grains until maturity (e.g. grain weevil or lesser grain borer) or complete removal of the germ by mites or moth larvae. Apart from this direct damage there are less direct effects of insect infestation such as webbing of grains together into small bundles, contamination with dead and rotting caterpillar bodies, production of very large quantities of dry excrement which appears as excessive dust, and tainting with bodily smell (mites). Most important of the forms of indirect damage, however, is the form of heating which is described later in this book as "dry grain heating" and all the trouble which this causes. Details of the more important insects which affect grain in storage and the damage which they do are given in later chapters.

LOSS OF GERMINATIVE POWER. For the miller, germinative power is of no direct importance, but it is being increasingly realized that germination is the most sensitive characteristic of grain and hence it is generally true to say that if the germination is good, the grain is completely undamaged from the point of view of milling. Millers who use in their grists considerable amounts of wheat harvested under difficult conditions (e.g. most English wheat) would be well advised to make germination tests as a regular routine.

Germinative power suffers as a result of heating, mould attack, or merely prolonged storage. The length of a period which can be called "prolonged storage" is very variable indeed. It depends for practical purposes solely on temperature and water content; high temperature or water content shortens the safe period to a matter of days while low temperature or water content may extend the period for many years. The mechanism by which prolonged storage under

reasonable conditions destroys germinative power has never been properly explained, but results appear to be consistent with the idea that the grain has a certain potential life which is fixed by some unknown factors. The rate of metabolism of the living tissues of the grain determines the time needed for the grain to reach the end of its life, therefore conditions which increase the metabolism (i.e. high water content or temperature) shorten the life, while conditions which lower the metabolic rate lengthen the life. In addition, feeble seeds which are readily invaded by moulds are more likely to be killed in this way under conditions of high water content which favour mould growth.

Usually it is impossible to tell by inspection whether grain has suffered damage to its germinative power as a result of storage unless there has been serious heating in the bin accompanied by mould activity which dulls the appearance of the berry and darkens the embryo.

DEVELOPMENT OF ACIDITY. All grain becomes more acid during storage. The acidity occurs partly as a result of hydrolysis and oxidation of fats (giving rise to fat acidity) and partly as a result of changes in the mineral constituents. Fat acidity has been shown to be closely correlated with the tendency of grain to deteriorate in storage but probably it is more correct to say that it measures the amount of deterioration which has already occurred. Since chemical deterioration is largely effected by development of micro-organisms, a measure of the amount of damage which they have done is likely to measure also the number of active organisms and the enzymes they produce. Hence fat acidity can be a useful measure of the future life of grain. However, in order to determine fat acidity the grain must be ground, the fat extracted with a suitable solvent, the solvent evaporated, and the free acid in the fat titrated. The procedure does not at present lend itself to rapid determination.

Acidity, especially of the fats, is not only a useful measure of the future behaviour of grain, it is also in itself a defect from the point of view of the miller, particularly if he is making a high extraction flour which will contain most of the fat in the grain. The circumstances which promote development of fat acidity have not been ascertained by careful testing from this point of view alone, but other storage tests in which determinations of fat acidity were made have shown that storage at a high water content is the most potent cause. There appears to be some correlation between the amount of mould or mouldy taint which is present and the acidity of the fats.

GLUTEN DETERIORATION. While changes in the protein constituents of flour are known to occur in storage, sometimes an improvement at first but later always a deterioration, very little investigation has been made of the effect on whole grain. Those who have studied the phenomenon in flour, and who have included whole wheat in their tests, are agreed that the changes are very much smaller and slower in grain than in flour. There is abundant evidence that wheat can be

stored, if conditions are ideal, for many years without any measurable changes in gluten quality. Under poorer conditions of storage it is probable that mould damage causing serious changes in flavour would set in long before serious damage to gluten quality took place.

LOSS OF NUTRITIVE QUALITIES. There is no doubt that some of the chemical changes which occur in grain during storage result in changes in the nutritive value of flour made from it. There has been surprisingly little work done on this subject in spite of its importance but a useful review of the literature from the standpoint of animal nutrition was published by Jones, Fraps, Thomas and Zeleny in 1943 (7th Report of Committee on Animal Nutrition, National Research Council Reprint, No. 116, March, 1943).

The mineral constituents are very little affected during storage, though the phosphorus may tend to become more soluble. The carbohydrates change very little unless the grain (particularly wheat) is damp enough to promote appreciable increase in the diastase content, in which case maltose and dextrose are produced at the expense of starch. The starch of rice may become more digestible during storage.

Fats break down fairly rapidly during storage, causing a rise in fat acidity. The fat content of cereals is low, however, and the process can proceed quite a long way before there is an appreciable change in palatability but it is perhaps possible that the increase in acidity might be sufficient in some cases to interfere with vitamin A uptake.

Proteins, as stated above, change very slowly in whole grain, and from the standpoint of nutrition there is probably negligible change in wheat protein in four years' storage under good conditions. Maize appears to be somewhat less stable and a definite decrease in the growth-promoting quality of the proteins has been shown to occur in storage particularly in the early stages. Mouldy and insect-damaged maize has been shown to be less effective in fattening pigs than fresh grain; it is quite possible that a similar effect might be shown for wheat.

Some vitamins certainly change in storage. Vitamin A is known to be destroyed in storage, but of course cereals generally (except maize) are not an important source of this vitamin. Of the vitamins of the B group, Thiamin and Riboflavin both have been shown to be stable in store. Vitamin E also appears to be stable in whole grain though it is gradually destroyed in cereal products.

CHAPTER 2

THE PHYSICS OF A GRAIN BULK

There are few other commodities, and probably no other living materials, which are commonly stored in such large bulks as grain. It is possible to store grain in this way because it is normally so nearly inert, but the fact that occasionally it breaks out in heating or insect infestation or other form of deterioration, makes it quite important that we should know something of the physical characteristics of grain in bulk, especially since the large size of the bulks exaggerates every physical factor.

The physical conditions within a grain bulk are dominated by three factors :

1. The low thermal conductivity of grain.
2. The water-absorbing power of grain which causes it to assume an equilibrium water content depending on the relative humidity of the air.
3. The porous granular nature of bulk grain.

Thermal Conductivity

Any material has a characteristic thermal conductivity which measures the rate at which heat passes from warmer to cooler parts. In a homogeneous solid conductor, heat passes equally rapidly in all directions and the thermal conductivity is independent of the size or shape of the particular piece of material examined, but in a granular water-absorbent material, the size and shape of the hot parts affects the amount of heat passing each unit of cross sectional area. Heat is conducted from grain to grain at the points where they touch and also through the intergranular air. It is also conveyed by micro-convection between adjacent grains and by large scale convection involving mass flow of intergranular air. In addition, some heat is transferred by radiation and by evaporation and condensation of water.

It is thus clear that " conduction " of heat through grain is a complex process. Probably the amount of heat leaving a hot zone in a grain bulk depends to some extent on whether conditions are favourable for large scale convection or not, so that determination of thermal conductivity in a laboratory does not make possible an exact answer to questions involving heat transfer in grain bulks. Nevertheless, if the determination is made under conditions which approximate to those met in practice, the result may be used with caution for many useful calculations of heat movement. For this reason, the writer made a series of determinations of the thermal conductivity of wheat, maize and oats, using concentric spheres as

the standard conducting surfaces (Oxley, 1944, b.). The results disagreed slightly with earlier determinations made between parallel plates, e.g. Bakke and Stiles, (1935), but have since been confirmed exactly by Babbitt (1945) for wheat. The writer's results were as follows :—

Material	Water Content	Thermal Conductivity
No. 1 Manitoba Wheat	11·7%	0·00036 c.g.s. units
Damp, mouldy, Manitoba Wheat ...	19·5%	0·00037 „ „
No. 1 Northern Manitoba Wheat ...	12·5%	0·00041 „ „
English Wheat	17·8%	0·00039 „ „
Yellow Maize	13·2%	0·00042 „ „
White English Oats	12·7%	0·00031 „ „

These figures are useful for purposes of calculation of temperatures produced by various conditions in masses of grain. It is interesting to note that other materials of similar thermal conductivity to bulk grain include dry soil (0·00033 c.g.s. units), soft wood with the grain (0·00031) and infusorial earth (0·00034). Grain cannot, therefore, be classed with either a typical heat insulator, such as cork, whose thermal conductivity is about one-third that of bulk wheat, or with a typical building material such as concrete, whose thermal conductivity is six to ten times as great as that of bulk wheat. As pointed out above, however, grain occurs in very much larger bulks than most materials and hence the resistance to escape of heat from the centre of a typical grain bulk is very high and even minor sources of heat are sufficient to cause serious rises in temperature.

Knowing the thermal conductivity, it is possible to calculate the minimum rates of heat production which are required to produce dangerous temperatures in bulks of various sizes. The appropriate formula for heat distribution in a sphere all parts of which are themselves producing heat will be useful. It is quoted below from Awbery (1927).

$$t_1 - t_2 = \frac{Q}{6K}(r_1^2 - r_2^2)$$

where t_1 and t_2 are temperatures at radii r_1 and r_2 from a centre. Q = heat production per unit volume per unit time and K = thermal conductivity. The appropriate c.g.s. units are the centimetre, gram calorie, second, and degree centigrade. If the British units are preferred, the appropriate ones are feet, British thermal units, hours, and degrees Fahrenheit and, in this case, the thermal conductivity figures given above should be multiplied by 2,905 to bring them to British units of thermal conductivity.

Thermal Diffusivity

Calculations of the type shown above give final equilibrium temperatures but say nothing about the rates of temperature change and in some cases these may be so slow that the final equilibrium

state may never be reached. In order to calculate possible rates of temperature change, it is necessary to know the specific heat and the density of a material as well as the thermal conductivity. The two may then be combined to give a characteristic of the material known as the thermal diffusivity, a quantity which measures the rate at which temperature changes, as distinct from quantities of heat, will pass through it. The relation between these is given by

$$x = \frac{K}{cd}$$

where x = thermal diffusivity (in.^{2} per sec. or cm.^{2} per sec.)

K = thermal conductivity

c = specific heat

d = density (" bulk " density, not the density of individual grains.)

Babbitt (1945) has recently determined the thermal diffusivity of wheat. That of maize and oats is still unknown but it could be easily calculated using the thermal conductivity figures given above, if the specific heat and density were determined. Babbit finds that the thermal diffusivity of Manitoba wheat is 0·00115 cm.^{2} per second (=0·00018 in.^{2} per second), and it may be assumed that that of other wheats is similar. Babbitt states that the specific heat of his sample was 0·37 (water = 1) which is rather lower than the commonly accepted figure of 0·4 to 0·45, and the density was 0·85 (water = 1) which is the equivalent of 68 lbs. per British bushel. In spite of the unexpectedly low specific heat and the high density, the figure for thermal diffusivity, which was determined directly, is probably quite accurate.

Using this figure, approximate answers may be found to some practical questions concerning bulk grain. Such a question is: A silo bin full of grain is heating owing to insect infestation and is fumigated. How long should it take to cool down? This question has frequently been asked because the rate of cooling is slow and if a theoretical expectation is available by which to check the cooling from time to time it is possible to decide whether, for example, fumigation has successfully controlled an insect infestation or not.

The following tables, which are based on data presented graphically by Fishenden and Saunders (1932), enable calculation of the theoretical cooling rate at the centre of a cylindrical or square silo bin. The left hand column of Table I or the right hand columns of Table II give the actual amount of cooling divided by the original difference in temperature between the hot wheat and the surroundings. Thus, for example, figures opposite 0·5 in the left hand column of Table I can be used to calculate the time required for the wheat to cool half way from its original temperature to the temperature of the surroundings. Table II is best used to calculate what amount of cooling may be expected after a given time.

TABLES I AND II

Data for calculating rates of change of temperature in square or round silo bins full of wheat assuming:

Thermal diffusivity = 0·00018 in.^{2} per sec.
t_o = original temperature of wheat
t_1 = average temperature of surroundings.
t_c = temperature at centre after T hours.
d = width or diameter of bin in feet.

$\frac{t_c - t_1}{t_o - t_1}$	$\frac{T}{d^2}$ Round Bin	$\frac{T}{d^2}$ Square Bin
0·90	4·5	5·6
0·75	7·0	8·3
0·50	11·1	13·5
0·25	17·9	22·8
0·10	27·5	34·5

$\frac{T}{d^2}$	$\frac{t_1 - t_c}{t_1 - t_o}$ Round Bin	$\frac{t_1 - t_c}{t_1 - t_o}$ Square Bin
6	0·80	0·88
8	0·66	0·75
10	0·55	0·65
12	0·45	0·56
14	0·37	0·47
16	0·30	0·40
18	0·25	0·37
20	0·21	0·29
25	0·13	0·20
30	0·078	0·14
35	0·047	0·095

EXAMPLE: Suppose a square bin of hot wheat was fumigated eight weeks ago and was then at 102° F. It has one outside wall and its other three sides are bins which have been empty most of the time or have contained cold wheat for short periods. The average outside temperature has been 46° F. and the grain is still at 75° F.; is this to be expected or are insects still alive and generating heat? The bin is 10 feet square.

Eight weeks = 8 × 168 = 1,344 hours
d^2 = 10 × 10 = 100 square feet
therefore T/d^2 = 13·44
from the tables this corresponds to a temperature drop of just over 0·47.

The actual temperature drop is $\frac{102 - 75}{102 - 46} = \frac{27}{56}$ 0·482

which is almost exactly what was expected. There is thus no evidence that spontaneous heating has occurred.

Babbitt has used his data to calculate another interesting point, namely, the depth in a grain mass to which daily and annual temperature changes will penetrate. Assuming approximately flat horizontal bulks of wheat of relatively infinite vertical and horizontal dimensions (i.e. all dimensions greater than about 20 feet) he comes to the following conclusions:

1. If the day to night temperature change is about 20° F., it will be reduced to 1° F., i.e. it will be scarcely detectable, at a depth of 5·1 inches.

   Daily fluctuations therefore do not penetrate below 6 inches to an appreciable extent.

2. If the annual mean temperature range is 77° F., which is approximately true for Port Arthur in Canada, the range is reduced to 1° F. at a depth of about 13 feet. In Britain the usual mean temperature range over the year is about 20° F., which is reduced to 1° F. at a depth of about 9 feet.

   In this country, therefore, we cannot expect any measurable change in temperature from summer to winter in the centre of bulks greater than 18 feet deep and wide, and changes will be very small even in smaller bulks.

In addition to the reduction in temperature range, with increasing depth the advancing temperature wave is so much slowed by bulk wheat that at 5½ feet depth it will be three months behind, and at 11 feet it will be six months behind! Therefore, the slight amount of summer warmth which penetrates to 5½ feet depth in a bulk will result in the grain being warmest at that depth in November or December. This delay is quite commonly noticed in grain stored fairly deep on floors even at less depths. It sometimes gives an impression that there is spontaneous heat developing when weather is cold in October or November, for the grain can then be felt to be quite warm to the hand even at a depth of only a few feet.

Convection

The role of convection in heat transfer in bulk grain is very difficult to assess. The writer, in one of his experiments (Oxley, 1944), prevented convection by means of paper baffles, and Babbitt (1945), by changing the position of his apparatus, also sought to estimate the importance of convection. In both cases it was concluded that convection plays only a very small part in heat movements. It must be remembered, however, that both these experiments were on a laboratory scale and it is possible that convection in a granular material is a phenomenon to which a large scale effect applies. No adequate mathematical or experimental treatment of this phenomenon has ever been made and further information will not be available until the expectations given by Tables I and II above can be accurately checked with measurements made on a full-scale.

The writer's observations of temperature distribution in hot silo bins certainly show that convection has a measurable effect in bringing hot air to the top of a bin, whence it can sometimes escape through the manhole, but it is impossible to say what is the magnitude of this effect in comparison with conduction.

The above remarks, of course, apply only to natural convection, i.e. to air movements due solely to the increased buoyancy of warm air. Forced convection, in which air is moved through the grain by

external power, whether by a mechanical blower or by wind cowls, is quite a different matter. This is dealt with in Chapter 5. For the moment, it is sufficient to say that even very slow forced convection movements are sufficient to remove all the heat which grain or insects can produce.

Movement of Water in Temperature Gradients

The phenomenon of translocation of water when temperature gradients are set up is one of the most important in grain storage technique. Whenever a mass of grain has parts at different temperatures, there is a movement of water from the hotter to the cooler parts. This movement is quite negligible, however, unless the temperature gradient is very steep, i.e., when hot and cool parts are close together.

Trouble due to water movement is, therefore, only common where warm grain comes into close contact with cool surfaces or air currents. Most usually this happens at the surface of a hot bulk, where cold air produces a steep temperature gradient, or where iron girders etc. pass through a hot bulk. Another common example of translocation of water is met when warm grain in bags " sweats," particularly at the bottom if the bags are stood on a cool, highly conducting floor such as concrete or stone. This " sweating " often gives the impression that the grain as a whole is damp, which is particularly puzzling if it is not understood, when it occurs in grain fresh from a drier.

It is important to understand exactly how this translocation of water occurs. All grain contains water, usually quite a lot; even in dry grain 10 to 13 per cent. of the weight is water. This water in the grain produces water vapour until it is in equilibrium with the water vapour in the atmosphere; grain of a particular water content always exchanges water vapour with the atmosphere until a particular relative humidity is reached. (See Chapter 3).

The relative humidity which corresponds to a particular water content varies somewhat from sample to sample of grain, but in any one sample the corresponding relative humidity is very little affected by temperature. But at any one relative humidity, air at a high temperature contains much more water vapour than at a low temperature. Therefore, if a sample of grain is heated, it must give up water to the air between the grains in order to keep the relative humidity of the air approximately constant. Similarly, if grain is cooled, it will absorb water from the air in contact with it.

Now if a vessel containing some grain, of the same water content throughout, is made hot on one side and cool on the other, the relative humidity of the air between the grains will remain almost unchanged from one side to the other because, as stated above, temperature has little effect on the humidity equilibrium of grain. But on the hot side, the air contains a great deal of water vapour, while on the cold side, it contains very little, so that the temperature gradient is matched by a gradient of air water content. Air diffuses continually throughout the vessel and both by this means and by

convection, hot air is continually entering the cool region while cool air enters the hot region.

Hot air on being cooled increases in relative humidity and must, therefore, give up some water to the surrounding grain in order to restore its humidity to the proper equilibrium value. Conversely, cool air on being warmed decreases in relative humidity and absorbs water from the grain. Thus, in the differentially heated vessel, air which diffuses or flows into the cool region is continually giving up water to the grain while air entering the hot region continually absorbs water. This will continue until the grain in the cool region is wet, and in the hot region so dry, that a gradient of grain water content is established which corresponds to a gradient of relative humidity such that the water content of the *air* is constant throughout the vessel.

This final equilibrium state has never been demonstrated in practice but the general effect has been studied by the Russian workers Kizel, Vasileva, and Tsygankova (1939) and by the Canadians, Anderson, Babbitt, and Meredith (1943). The Russians immersed a cooled glass tube in a small bulk of grain maintained at normal temperatures and measured the increases in water content of grain adjacent to the tube. The Canadians maintained a temperature differential of 35° C. (63° F.) between the two ends of a box six feet long for ten months. Both sets of experiments showed clearly that translocation takes place as described above and that it is quickest when the temperature gradient is steepest. In the case of the Russian experiment, and possibly at the cold end of the box used by the Canadians, it is likely that actual dew was formed on the cold surfaces and subsequently absorbed by adjacent grain. This means that air against these surfaces is cooled below the temperature at which its relative humidity reaches 100 per cent. Some writers on this subject have spoken as though actual condensation and dew formation at the cool end of a gradient are essential for water translocation, but the account of the mechanism given above shows that this is by no means so. Dew formation occurs only when the gradient in temperature is exceedingly steep.

Diffusion and Flow of Intergranular Air

Both diffusion and mass flow of air have been referred to in the above discussion, but little has been said about their relative importance in ventilating the intergranular atmosphere. Grain is a living material continually absorbing oxygen and producing carbon dioxide. In this it is reinforced and often over-shadowed by micro-organisms and insects. If there are no air movements the only process which can renew the oxygen supply to the grain and remove excessive accumulations of carbon dioxide is diffusion. The rate of diffusion of carbon dioxide through bulk wheat was measured by Dr. F. Y. Henderson and the writer in 1943 and found to be about one third of the rate in still air.

If K is the coefficient of diffusion

Q = quantity of carbon dioxide diffusing in milligrams.

L = length of diffusion path in centimetres.

a = cross sectional area of diffusion path in square centimetres.

t = time in seconds.

c = concentration of carbon dioxide in milligrams per cubic centimetre of air.

$$K = \frac{Q.L}{c.a.t.} = 0{\cdot}0415$$

in still air, K for $CO_2 = 0{\cdot}14$.

These figures mean that diffusion alone is excessively slow and it is not surprising to find that in conditions which do not favour air flow, carbon dioxide accumulates considerably in grain bulks.

Intergranular air flow occurs by convection when there are suitably distributed temperature gradients or by aspiration under the influence of barometric changes. If the barometric pressure changes by one inch of mercury, as it frequently does in the course of a day or two, the volume of the intergranular air changes correspondingly by about one thirtieth. This will cause an average penetration of fresh air from outside of about one eightieth of each linear dimension of the bulk, if air can enter on all sides, or of about one thirtieth of the depth if air enters only from the top, as in an approximately air-tight silo bin. Gas exchange of this type may be an important factor tending to aerate the intergranular atmosphere but can hardly have an appreciable effect on cooling.

For thermal convection to occur, there must be a lateral temperature gradient and an unobstructed, more or less vertical path for the upward and downward air streams through the hot and cool regions respectively. These conditions are usually met in a silo bin where loss of heat from the outer walls results in a cool peripheral zone for the downward stream and a hot central core for the upward stream. In large flat bulks, however, heat loss is predominantly vertical and there may be little lateral gradient. Even though the grain may be quite hot, there will be little convection if the heat is evenly distributed over the width of the bulk because there will be no adequate cool path for the downward stream. Thus it is a not uncommon condition for a large flat bulk, which is heating but appears to be perfectly well aired, to have a concentration of several per cent. of carbon dioxide in its intergranular atmosphere at mid-depth.

One further point concerning air movement in silo bins needs to be mentioned. Carbon dioxide is a heavy gas and if it accumulates above a few per cent., the intergranular atmosphere becomes heavy enough to leak quite rapidly through unsuspected cracks, loosely fitting slides, etc., at the bottom of the bin. If, however, carbon dioxide production is accompanied by heating, the expansion of the intergranular atmosphere as a result of heat lowers its density and thus tends to nullify the effect of carbon dioxide accumulation. In

fact, this compensation is surprisingly often *almost* exact so that the intergranular atmosphere in a hot bin is at a temperature which brings its density very near to that of the atmosphere. This may be taken to indicate that there are appreciable leaks in the particular bin so that a carbon dioxide accumulation would result in air " draining out " of the bin unless its temperature is correspondingly raised. In such a case the temperature probably determines the carbon dioxide concentration which can be reached in the bin.

CHAPTER 3

WATER RELATIONS OF CEREAL GRAINS

Moisture Content (or Water Content)

All discussion of grain storage is dominated by considerations of moisture content (the writer prefers the term water content). The concept of water content implies that grain consists of dry solid material plus a quantity of water which can vary within wide limits down to zero. This concept is sufficiently near the truth for most practical purposes, but as soon as questions of accuracy of determination are raised, it becomes important to recognize how far it is wrong to think of water and dry matter being merely mixed as distinct from combined in the chemical sense.

Water which is imbibed into a collodial material (such as grain), is usually said to be partly adsorbed. This means that some water is held relatively loosely by capillary forces in the fine interstices of the solid material (absorbed), while the rest is held much more firmly in very thin layers on all surfaces (adsorbed). These processes grade into each other and it is impossible to draw a sharp line of demarcation between adsorption and absorption.

The first water adsorbed onto a surface is held in the form of a monomolecular layer, that is, a layer only one molecule thick. Every molecule is therefore in direct contact with the adsorbing surface and is bound to it by powerful inter-atomic forces which are of the same order of strength as those which bind the constituent atoms of ordinary compounds. The next water adsorbed probably forms further monomolecular layers on top of the first, but the water molecules in these, though held quite firmly, are not in direct contact with the solid surface and are therefore held more loosely than those in the first layer. As further water is adsorbed, the forces of adsorption become rapidly less and are soon no greater than the capillary forces of absorption which then take over and hold the majority of the water.

If grain is ground and heated in a stream of dry air, or exposed for a long time to the action of a powerful desiccating agent, the majority of the water is removed, but it is a moot point whether all, or if not, what proportion, of the closely adsorbed water is removed. It seems probable that various compounds, particularly some hydrated materials containing water loosely combined, will break down to release water before the last surface-adsorbed water is removed, for the forces which adsorb the monomolecular layer of water are of an order not very different from those which combine water in many hydrates.

It is thus impossible to say with precision how much of the water

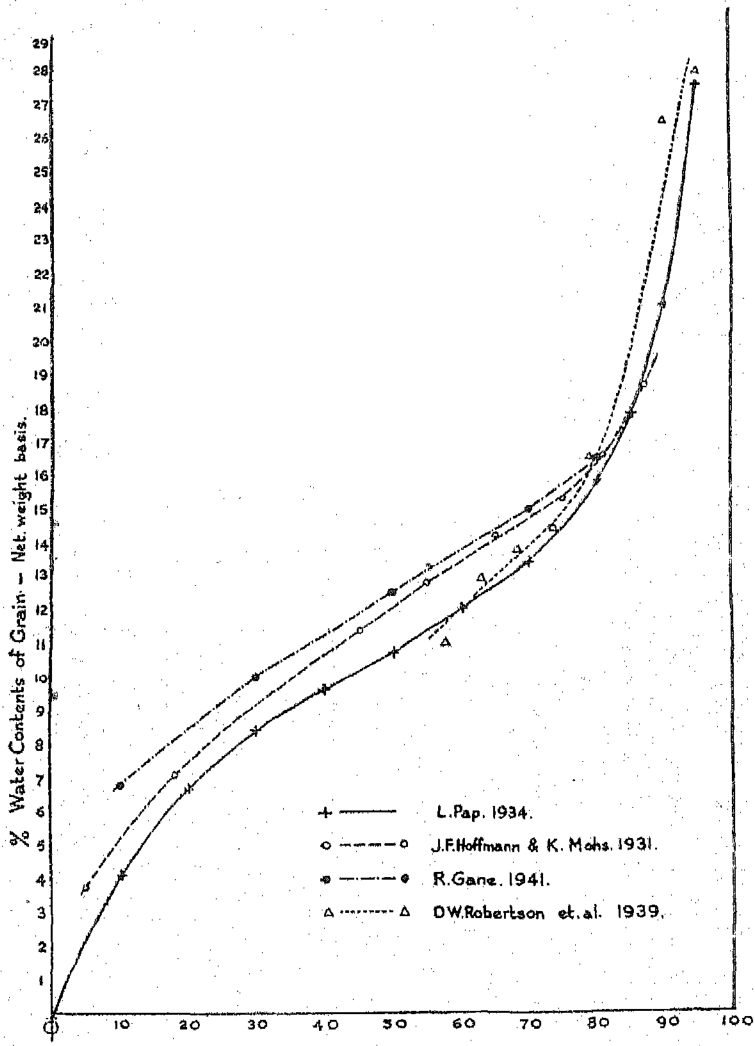
which is removed from grain by various methods of drying was absorbed, how much adsorbed, or how much was truly combined. It is clear that there can be no precise "correct answer" to any process of water content determination. For this reason the water content of grain, or of a grain product, can only be stated in terms of the result given by a specified method. Whenever precise determinations of water content are reported, the method used should always be described either by reference to a standard technique (e.g. official Brown Duvel or N.P.L. electric meter, etc.), or by a statement of the conditions (e.g. grain kibbled and dried at 110° C. for four hours).

Atmospheric Humidity and Grain Water Content

Water which has been absorbed into grain is no longer ordinary water. In addition to being no longer free to flow, it is of slightly higher density, slightly lower specific heat, and it exerts a very much lower vapour pressure. For practical purposes, it is only this latter difference from free water which is of importance. It means that the amount of water vapour contained in an atmosphere in equilibrium with grain is always less than that of an atmosphere in equilibrium with a free water surface at the same temperature. The lower the water content of the grain the more tightly the water molecules are bound and, hence, the less free they are to enter the atmosphere. Therefore, the relative humidity of an atmosphere in equilibrium with grain is lowest at low water contents and rises to approach 100 per cent. as the water content rises.

When the temperature of grain is changed, the vapour pressure exerted by its water changes (rising with rising temperature) in almost exactly the same way as that of a free water surface, so that the humidity of the grain atmosphere remains an almost constant fraction of that of a saturated atmosphere, i.e., the *relative* humidity remains almost constant. For many purposes it is near enough to say that the relative humidity of the grain atmosphere of a particular sample is independent of temperature, but if more accuracy is needed, or if a wide temperature range is to be considered, it is necessary to recognize that there is a slight increase in atmospheric relative humidity in equilibrium with grain as the temperature is raised. The temperature effect for wheat is approximately 0·6 per cent. to 0·7 per cent. water content decrease per 10° C. temperature rise at constant relative humidity.

Many workers have investigated the relation between grain water content and atmospheric relative humidity but have reported widely different results. To illustrate this, and the general type of the relationship, four sets of data are shown graphically in the accompanying figure. The data are from reputable workers and it is reasonable to give equal credence to all. They are L. Pap (1934), J. F. Hoffmann and K. Mohs (1931), D. W. Robertson *et al* (1939), and R. Gane (1941). In the figure, the line of closest fit to each set of data has been drawn by eye and the diversity of the results is obvious.



In spite of the diversity there is general agreement that the relationship is best represented by a sigmoid curve rising sharply above 80 per cent. relative humidity. There is also less disagreement in the region of 78-80 per cent. relative humidity ; this may merely reflect the fact that all the workers started with grain near this humidity and subsequently conditioned it upwards and downwards with varying degrees of success. There is no doubt that a better method of deriving this curve would be to condition wheat by addition of water (as liquid or vapour) and then, after allowing plenty of time to " settle down," to determine the relative humidity of the intergranular atmosphere.

The steep upward trend of water content at humidities above 75 per cent. is most significant for those who have to store grain in the British or similar oceanic climates. Normal humidities in Britain are in the neighbourhood of the inflection point of the curve, and quite small increases in relative humidity (such as are normal in western and northern parts of these islands) correspond to large increases in equilibrium water content. This means that in winter, in most parts of the country, and in the west and north at most times of the year, wheat is continually absorbing water when it is exposed to the atmosphere. In drier climates whose relative humidity seldom or never rises above the inflection point of the curve, changes in humidity have very little effect on the corresponding wheat water content, and absorption of water from the atmosphere is seldom of any significance.

Measurement of Water Content

Most methods of measurement of water content are based on the assumption that it is possible by some process (such as by heating or by chemical combination) to remove all the water from a sample and determine the amount removed by direct measurement, or by measurement of the loss in weight. Other methods measure some property of the grain (such as dielectric constant or equilibrium water vapour pressure) which is known to be correlated with water content.

It is clear from the earlier discussion that no real meaning can be attached to the concept of removing *all* the water from a sample of grain and to this extent methods based on this concept are at fault. The fault, however, is no greater than is inherent in the concept of "water content" itself and in fact the practical utility of water content determination overrules all purist objections.

It is not proposed to review all methods for determination of water content; such a review would be too long and the technique of every established method is already adequately described in other publications. It is, however, appropriate for the purposes of the present book to point out how the *principles* of the various methods differ and to relate them to the foregoing discussion.

How to Test a Method

Since water content must be expressed in terms of a standard method of determination it is well to have a means of deciding what method of determination it is best to choose. The writer suggests that the best criteria of a good method are:—

(*a*) Its ability to give repeatable results.

(*b*) Its ability to measure correctly the calculated changes in water content which result from the addition or removal of measured quantities of water.

It is clear that repeatability must be tested by making a number of determinations of water content on samples removed from grain contained in a sealed container. It is perhaps less clear how a test

for the satisfaction of the second criterion should be carried out and the following detailed directions may, therefore, be useful.

1. Obtain a sample of grain sufficiently large to permit removal of four or six samples for determination of water content. Mix the grain thoroughly and keep it in an airtight bottle.
2. Make duplicate or triplicate determinations of water content by the method to be tested. The mean of these determinations ($=a\%$) will be the best measure which the method is capable of giving of the initial water content of the grain.
3. Weigh the remaining grain accurately (weight $=A$ grams) and then expose it for several hours or even days to a thoroughly wet or thoroughly dry atmosphere so as to cause it to take up or lose water vapour. During this exposure the grain should be spread one grain deep so that the atmosphere has direct access to every grain. Reweigh the grain accurately (weight $=$ B grams) and return it immediately to the sealed bottle. If proper precautions have been taken to avoid loss of grain, or contamination by foreign bodies, during exposure, the difference between the two weights may be regarded as an accurate measure of the amount of water absorbed or lost by the grain.
4. Again make duplicate or triplicate determinations of water content by the method under test. The mean of these determinations is the best measure which the method can give of the new water content.
5. Calculate the expected new water content ($=b\%$) as shown below and compare it with that found by actual determination. If the determined change in water content (increase or decrease) is less than that calculated, the method under test is failing to measure all the water and appropriate changes should be made in the technique. In the case of oven or distillation methods the appropriate change will be an increase in temperature or time, or possibly in the fineness of grinding. Corresponding changes designed to increase the sensitivity to water would need to be made to other methods. If the determined change in water content exceeds that which is calculated, the method will need to be adjusted in the direction of reducing sensitivity to water.

The calculation of change in water content from the observed change in weight is conveniently made by the means of the following formula :—

$$b=\frac{Aa+100\,(B-A)}{B}$$

where the initial water content (on the wet weight basis) is $a\%$ and the weight of the grain before exposure to a wet or dry atmosphere is A grams. The weight of the grain after exposure is B grams and the calculated water content (also on the wet weight basis) is $b\%$.

This test can probably be satisfied by any of the water removal methods (oven, distillation, Karl Fischer, or calcium carbide) listed below if a suitable choice of conditions is made.

Notes on the Common Methods

OVEN METHODS.

Oven methods are the most popular because, properly handled, they give good repeatable results. They are, however, usually laborious, they require grinding of the grain, and standardization of procedure is most important. In the writer's experience, the suggested test cannot be satisfied by an oven method which uses a temperature below 105° C., unless the period of heating is extended to several days. Grinding of the grain is also essential unless the grains are isolated from each other and heated in a vacuum desicator to at least 125° C. for at least 48 hours.

DISTILLATION METHODS.

The basic assumption of a distillation method, namely, that heating for a certain time to a temperature well above 100° C. will remove substantially *all* the water, is the same as that of the oven methods. The use of an immiscible liquid to cover the ground grain probably prevents oxidation from producing spurious quantities of water, but probably does not affect thermal decomposition of compounds in the grain. The choice between oven and distillation methods must depend solely on convenience ; neither type of method has any theoretical advantage over the other.

KARL FISCHER REAGENT.

Recently, much attention has been given to the use of Karl Fischer reagent for determination of water in very many different materials including grain. This reagent makes it possible to determine water in alcoholic solution by simple titration, which can be very convenient for some purposes, but it must be remembered that a basic assumption underlies this method which is similar to that underlying oven and distillation methods. It is that *all* the water in a sample can be removed by treatment with dry alcohol (usually methyl alcohol), an assumption which is almost as much open to question as the removal of water by heat, though it is possible that there is less actual decomposition of hydrates by this method. Grinding the sample is, of course, essential.

CALCIUM CARBIDE.

A simple chemical method for removal of water from a ground sample of grain is to mix it with powdered calcium carbide, with which the water reacts to produce acetylene. The quantity of acetylene is measured either by loss in weight of the mixture or by increase in the pressure of the atmosphere over the mixture when the gas is not allowed to escape. It appears that the accuracy of this method depends in a high degree on the fineness of grinding. It does not give such consistent results as oven or distillation methods.

ELECTRICAL METHODS.

Electrical methods for determination of water content do not involve the assumption that water can be completely removed, but they do involve the similar assumption that the physical condition and distribution of the water in the grain is always the same at a particular water content, irrespective of variety or previous history. Because this assumption is unsound no electrical method can give results which are consistently related to those given by other methods or to other characteristics of the grain, e.g., humidity equilibrium. Nevertheless, for some purposes, especially where the operator can be assured that recent wetting or drying have not occurred, electrical methods can be very satisfactory and, of course, they are very quick.

It should perhaps be pointed out that different meters measure different electrical characteristics of the grain. The Tag Heppenstall meter measures pure resistance, for an electrical connection is made with the grains and a direct current is passed through them. All other meters, however, use alternating current and measure various combinations of resistance and dielectric constant whether or not there is an electrical connection between the grain and the electrodes or plates of the meter. Generally, dielectric constant is the quantity which varies most consistently with water content, but a combination of this with resistance probably gives the most satisfactory calibration.

METHODS BASED ON HUMIDITY MEASUREMENT.

As the earlier discussion shows, the relation between water content of grain and the relative humidity of an atmosphere in equilibrium with it is far from constant, but for very approximate measurements of water content a measurement of relative humidity may often be close enough. This method has the advantage that it can be applied to grain in bags or bulk without the necessity to take samples but, unfortunately, there are few reliable methods for measurement of atmospheric humidity. Nevertheless, development of simple, rough methods based on determination of atmospheric relative humidity may be expected.

The approximate nature of such methods may not always be a disadvantage, for there are occasions when relative humidity is a more useful quantity to measure than water content. Relative humidity largely determines the liability of grain to attack by fungi or insects and if it is desired to study these points, direct determination of relative humidity may have considerable advantages over determination of water content by conventional methods.

CHAPTER 4

VENTILATION OF STORAGE PLACES

It is widely considered that the amount of free access of air which is allowed to stored grain is a very important factor in determining its successful preservation. While it is true that there are circumstances in which free access of air may be useful, there is no doubt that popular opinion greatly exaggerates the virtues of ventilation. It is very important, therefore, that the effects of exposure to the atmosphere, or the complete exclusion of it, should be carefully considered.

The important effects of exposure of stored grain to the atmosphere are :

1. Exchange of heat,
2. Exchange of water vapour,
3. Exchange of carbon dioxide and oxygen.

But, in addition to these, it must be remembered that it is practically impossible to expose grain freely to the atmosphere without also exposing it to infestation by rodents or insects.

Clearly the access of air is only desirable when the exchanges will occur in the right direction, i.e., when the grain is hotter than the air so that it will lose heat, and damper than the air so that it will lose water. It is much less certain what constitutes a desirable exchange in the case of carbon dioxide and oxygen since the accumulation of the former gas may be expected to depress respiration rates and hence heat production. This point is discussed below in connection with airtight storage.

Natural Ventilation

In the writer's opinion, measures designed to " air " a storage place, in the sense that a room is " aired " by leaving doors and windows open are almost invariably useless. As has been shown in Chapter 2, gaseous diffusion and heat movement in grain are both exceedingly slow and, in the absence of mechanical means to force air through bulks, changes in the atmosphere at the surface have a negligible effect on the intergranular atmosphere and on the water content or temperature of the grain. In particular, the practice of leaving the top off a silo bin in order to air the contents is certainly useless, for heat loss through the opening is negligible, and even if there were an adequate opening at the bottom of a bin for air entry (which is never the case unless special provision is made), the production of carbon dioxide usually tends to keep the density of the intergranular atmosphere equal to that of outside air in spite of any heating which may occur. There is thus very seldom any tendency towards mass convection so that the provision of an opening at the

bottom of the bin would seldom have any effect in improving the aeration of the grain. The practice of leaving the lids off closed-top silo bins is not only useless but is to be deprecated because it tends to admit insects and dust.

There is one condition in which it may be desirable to open the doors and windows of a floor storage or lift the lids of silos; that is when the grain is already very hot and is producing appreciable steam. When this happens, the fabric of the building (especially of a wooden building) may be seriously damaged by condensation, and a free circulation of air will minimize this risk. The windows *are opened* in this case solely for the benefit of the building, for no amount of natural ventilation will have any effect in cooling a bulk of grain which is in an advanced stage of heating. It may also sometimes be worth while to arrange for ventilation of the upper surface of a hot bulk in order to dry off the damp grain which develops at the surface as a result of translocation of water.

Bag Storage

Bag storage is a somewhat different case from bulk storage, from the point of view of ventilation, because the smaller dimensions of bags permit appreciable water vapour and heat exchange, provided that the bags are arranged so that air can circulate reasonably freely round them. There is probably little to choose, however, between a closely packed stack of bags with very few air spaces and a bulk of grain of similar dimensions. If bags can stand separately or are stacked with ample air channels they may have considerable advantages for short period storage of excessively damp or hot grain.

The effect of the small dimensions may be seen by calculating the rates of heat loss from bags and comparing them with those for silos which were given in Chapter 2. A 2-cwt. bag standing vertically approximates to a cylinder 2·6 feet high by 1·48 feet in diameter and may be treated as a small round silo bin. The cooling of this may be compared with that of the silo bin given in the example on page 10. In this, wheat at 102° F. required eight weeks to cool to 75° F. when the surrounding air temperature averaged 46° F. By interpolation in Table II on page 10 T/d^2 is found to be 11·36 for this rate of cooling. Since $d = 1{\cdot}48$ feet, $T = 11{\cdot}36 \times 1{\cdot}48^2 = 24{\cdot}9$ hours.

This calculation is made without making any allowance for the loss of heat from the top and bottom of the bag, but in spite of this it seems that a 2-cwt. bag, freely exposed to the atmosphere, will cool in 25 hours at least as much as a 10-foot square silo bin will cool in eight weeks. While rapid dissipation of heat in this way is a very clear advantage of temporary bag storage, the danger of translocation of water to any point where the bag touches materials of high thermal conductivity (e.g., concrete, stone, or metal) must not be forgotten. Hot grain in bags can only be safely allowed to cool if it is standing on a wooden floor or is otherwise insulated from paths of rapid heat loss.

It is common practice to open the tops of bags containing warm or

damp grain. While the writer knows of no measurements having been made to test the effect of this practice, it seems very improbable that it has any effect at all. There may be an indirect effect, however, for if bags are left open, they cannot be piled on top of each other and must be stacked singly, thus improving the ventilation. An order to leave the tops of bags open is thus merely an order not to stack the bags too closely.

Airtight Storage

The fact that there is nothing to be gained by encouraging free air circulation in grain storage places has quite frequently led to the suggestion that the reverse policy should be adopted and grain stored in airtight containers. This policy was strongly advocated, for example, by Dendy and Elkington (1918) as a result of their experiments during the 1914-18 war.

The ideas behind the suggestion are:

1. That carbon dioxide produced by respiration of grain and attendant organisms (including fungi and insects) will accumulate and oxygen be depleted until all metabolic processes are brought to a standstill. This, it is suggested, will prevent heating, insect development and all kinds of deterioration.
2. Storage which is airtight is also proof against insects and rodents.
3. In damp climates uptake of water by dry grain from a moist atmosphere is prevented.

Against these attractive ideas, which appear to suggest a means of storing grain indefinitely, must be set a number of facts which seriously weaken the arguments of the advocates of airtight storage. In the first place, while accumulation of carbon dioxide with a corresponding depletion of oxygen certainly depresses metabolic activities, and will ultimately kill insects and rodents, it causes anaerobic respiration of the grain tissue and encourages anaerobic micro-organisms. Anaerobic respiration of grain tissue is likely to lead quickly to its death and dead grain goes mouldy and rots very quickly. In any case such storage would not be suitable for seed grain. Secondly although experiment has shown that visible mould growth is inhibited by airtight storage, some organisms certainly survive the anaerobic conditions and produce strongly alcoholic or acidic odours. Damp grain appears to be rendered useless as quickly under anaerobic conditions as in free air.

In the United States a type of damage known as "sick" wheat has been recognized for some years. It appears without any sign of heating and is characterized by a dull, lifeless appearance of the grains and a dark, nearly black, colour of the germ. Viability is completely destroyed and the acidity is high. Mould in the crease or on the germ is often associated with sick wheat but is said not to be invariably a feature. Bread quality is inferior to that of normal wheat, though, surprisingly, the deterioration from this point of view is not as serious as might be expected.

The general description of this form of trouble is very strongly suggestive of what would be expected if the germ of grain had died under anaerobic conditions. This has led several workers to suggest that "sick" wheat is due to storage with insufficient aeration. This has not finally been shown to be the case in any actual store, but Carter and Young (1945), were able to reproduce the type of damage by storage in airtight containers at high water contents and there seems little reason to doubt that inadequate ventilation is at least a predisposing cause. Recently, Milner, Christensen, and Geddes (1947) have confirmed this finding but have also shown that fungal development can be partially responsible for the deteriorative processes which cause sick wheat. They believe, however, that fungi are not always involved.

It is clear that airtight storage cannot ever be recommended in any case where the water content may be high. Probably dry grain would keep longer in airtight storage than in free air and, if very long period storage is contemplated, controlled minimum aeration of the bins may be worth trial. For ordinary purposes, the provision of special airtight or semi-airtight bins for storage of dry grain seems quite unneccesary.

A third objection to airtight storage is the difficulty of producing really airtight storage bins on a large scale. Certainly it is not impossible but there seems to be no case to justify the trouble and expense.

CHAPTER 5

FORCED VENTILATION OF BULK GRAIN

Most of the inefficacy of ordinary ventilation is due to the fact that air will not circulate naturally through grain. When, however, blowers can be used in conjunction with suitably designed bins so as to force air through the grain, the circumstances are entirely different. A relatively small power is sufficient to produce an air flow of two to five feet per minute through a bulk, and even these low rates of flow are sufficient to permit considerable exchanges of heat and water vapour between the grain and the atmosphere.

The Cooling Effect of Ventilation

Table III shows the volumes of air per unit volume of grain needed to remove all the heat produced under various conditions.

TABLE III

Volume of air per unit volume of wheat per minute needed to remove all the heat produced.

Heat production per c.c. per minute gram calories	Mean difference of temperature between the grain and the entering air		
	20° C.	5° C.	1° C.
5×10^{-4}	0·084	0·33	1·67
2×10^{-4}	0·033	0·13	0·67
$0·6 \times 10^{-4}$	0·010	0·04	0·20

If the conditions are those of the first column (20° C. temperature difference), the grain will remain hot but further heating will be checked. If the temperature difference is restricted to 5° C. or 1° C. the warmth will be almost indetectable.

The top horizontal row (5×10^{-4} calories) is an extreme figure for heat production very unlikely to be exceeded or even reached by the dampest grain for which bulk storage would ever be contemplated. Even the middle line (2×10^{-4} calories) represents a high figure for which, however, allowance should probably be made. The bottom line ($0·6 \times 10^{-4}$ calories) represents a high normal rate of heating which should be budgeted for in any ventilation plant.

On this basis it seems reasonable to recommend that a forced ventilation installation, designed to keep grain from heating, should provide for an air flow of 0·2 volumes per unit volume of grain per minute (i.e. about 9 to 10 cubic feet per ton per minute). This should restrict the mean temperature difference between the grain and the

incoming air to 1° C. in the case of the vast majority of parcels of grain and would not permit it to exceed about 8° C. in the worst cases.

The air velocity required will be proportional to the depth of grain; an air flow of 0·2 volumes per unit volume of grain per minute corresponds to a velocity of two feet per minute through grain ten feet deep. Since the air pressure needed to force air through grain increases slightly more than proportionately to the depth, and the volume needed is directly proportional to the depth, it follows that the power needed is proportional to slightly more than the square of the depth. It would, therefore, normally be advantageous to avoid great depths in bins intended for forced ventilation.

The above calculation of the cooling effect of an air stream has assumed that there is no drying effect. The conditions which determine whether drying will occur or not are discussed below, but here it should be noted that when grain is hot and there is a big difference in temperature between it and the incoming air, there will nearly always be some drying effect however damp the incoming air may be. The evaporation of water which accompanies drying absorbs a considerable amount of heat, so that the overall cooling effect of an air stream is much greater when grain is hot. This provides a factor of safety which should cover the most exceptionally high rates of heat production which might occur.

The Drying Effect of Ventilation

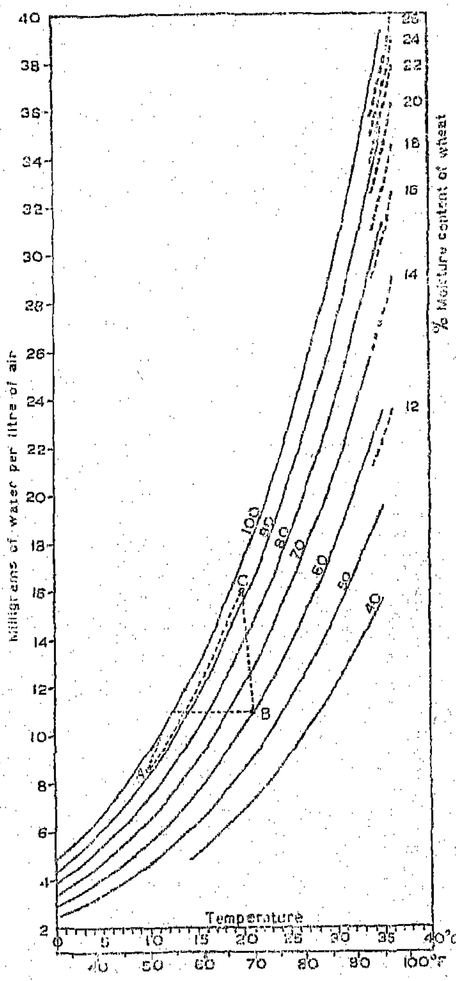
If the relative humidity of the air stream passing through grain is lower than the equilibrium relative humidity (see Chapter 3) the grain will be partially dried. The relative humidity of an air stream, however, is very much affected by its temperature and therefore the thermal relationships between air and grain are very important.

In general, the sequence of effects which follow when air is forced through grain fall into three phases:

1. Grain temperature at first unchanged but soon changing to approach that of the incoming air.
2. A partial equilibrium state with the grain temperature close to that of the incoming air but remaining slightly different from it until humidity equilibrium is reached.
3. The final equilibrium state when grain is in humidity and temperature equilibrium with the air and no further changes occur.

Phase 1, which is distinguished by the fact that there is a considerable temperature difference between grain and air, is very important, because at this stage there may be a rapid deposition of water on the grain or rapid drying. In order to determine what effect may be expected, the curves given in Fig. 2 may be used. The curves are the familiar family which exhibit the relationship between air water content and air temperature at various degrees of saturation

(relative humidity). In addition, the positions of relative humidity curves which correspond approximately to grain water contents of 12 per cent. to 26 per cent. have been indicated on the figure.



The nature of the successive phases of the approach to equilibrium can be found quickly by means of the curves as is illustrated by the following examples :

EXAMPLE 1.—Grain of 22 per cent. water content at a temperature of 50° F. (point A on the graph). Air of 60 per cent. relative humidity at 70° F. (point B on the graph).

In the first phase, the incoming air impinges on the cooler grain and is cooled to approach the temperature of the grain. But this

takes the air above the 100 per cent. humidity line, i.e., it becomes supersaturated, and dew will be deposited on the grain. Later in this phase, the grain is gradually warmed up towards the temperature of the incoming air. As the grain is warmed, its equilibrium relative humidity remains nearly constant so that the water content of the intergranular air follows a line parallel with the curves until it reaches point C., with its temperature close to, but slightly below that of the incoming air. The water content of the intergranular air which escapes from the bin is now much higher than that of the incoming air, so that on balance more water leaves the grain than enters it, and hence the grain is dried. As drying progresses, the rate of evaporation falls and hence the corresponding difference of temperature between the grain and the air decreases and ultimately the grain and air come into full equilibrium at point B. The successive changes in the air passing through the grain are represented by the dotted line B, A, C, B.

Example 2.—Grain of 19 per cent. water content at 75° F. Air of 85 per cent. relative humidity at 50° F. It will be seen that the relative humidities are nearly identical and only the temperature difference is effective. In the first phase the air is warmed by passing over the warm grain and its relative humidity is correspondingly lowered to below 40 per cent. This results in immediate drying of the grain, but as the grain is cooled by the direct effect of the cool air, and by absorption of heat by evaporation of water, the humidity of the entering air falls until complete thermal equilibrium is reached. Owing to the slight drying which occurred in the first phase, the grain humidity will be temporarily lower than that of the air so that water will be absorbed again until all which was lost is regained.

A number of examples may be worked out in this way and it will be seen that the following rules apply:

1. The immediate effect of passing air over grain depends on the relative humidity of the atmosphere *when its temperature is changed to that of the grain.* If it is then higher than that of the intergranular atmosphere water will be deposited, if it is lower, water will be evaporated.
2. The ultimate effect of passing air over grain depends solely on the relative humidities of the intergranular atmosphere and the entering air provided that the air stream determines the temperature of the grain. If this condition is satisfied air may be warmed before it enters the grain in order to lower its relative humidity and thus effect considerable drying. If there is any source of heat or channel for loss of heat which keeps the grain temperature above or below that of the entering air, the ultimate effect must be found by applying the rule for phase 1, for this phase is still in operation so long as the temperature remains different from that of the entering air.

From this it is clear that the results of forced ventilation depend very greatly on the extent to which the grain in a ventilated bin is

thermally insulated from its surroundings since with low rates of flow such as it is economically sound to use, the air stream carries little heat. The mass of the grain in any ordinary sized bin (greater than 6-8 feet across) is sufficiently insulated by its own poor thermal conductivity, but at its surface (i.e. against the bin walls), the temperature is likely to be almost entirely controlled by the temperature of the surroundings. If warmed air is being used in order to expedite drying, grain next the walls of a bin, particularly of a metal bin, will often become damp and caked. This is a serious objection to the use of metal bins in any case where an attempt is being made to dry grain by the use of pre-warmed air. If metal bins are used for this purpose they should certainly be lagged on the outside.

The Relative Humidity of the British Atmosphere

If no attempt is to be made to warm or dry air before blowing it through a bulk of grain, the results to be expected will depend on the mean relative humidity of the air available. Table IV gives data for five stations in Britain. It will be seen that, during the winter months, the mean relative humidity is seldom below 80 per cent., and is usually close to 85 per cent. which corresponds to wheat water contents in the region of 17 per cent. to 19 per cent. The lowest average humidity for any month at these stations is 72 per cent. for June in south-east England (Kew) and even this corresponds to about 15 per cent. water content. There is thus no possibility of drying grain to a safe water content for permanent storage merely by passing air through it unless the air is pretreated in some way.

TABLE IV

Monthly means of relative humidity at 5 stations (1886-1915)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	%	%	%	%	%	%	%	%	%	%	%	%
A	80·7	79·6	78·7	78·0	78·5	78·1	78·5	79·5	80·3	82·4	82·1	82·3
G	84·9	83·2	79·8	75·8	74·4	75·5	77·7	79·8	81·7	83·2	84·6	85·5
E	87·7	86·4	82·9	79·9	79·6	78·1	82·0	84·0	84·0	85·6	86·5	88·4
K	84·5	81·6	79·3	74·7	73·4	72·8	73·0	75·8	79·2	84·6	85·9	85·9
F	83·8	81·7	81·3	79·6	80·2	81·4	81·6	82·9	84·2	85·2	83·8	84·1

A = Aberdeen.
G = Glasgow.
E = Eskdalemuir (Dumfries).
K = Kew.
F = Falmouth.

TABLE V

Daily change in atmospheric relative humidity and in air water content (mg. per litre) in October, January and April at Kew Observatory.

Time	October		January		April	
	Relative humidity %	Air Water content mg/l	Relative humidity %	Air Water content mg/l	Relative humidity %	Air Water content mg/l
0h....	90·0	7·7	86·4	5·3	83·4	6·2
2h....	90·7	7·6	86·6	5·3	85·5	6·1
4h....	91·3	7·6	86·5	5·2	86·9	6·0
6h....	91·3	7·5	86·8	5·2	86·7	6·0
8h....	89·4	7·6	86·7	5·2	79·9	6·3
10h....	82·6	8·1	85·4	5·4	70·2	6·4
12h....	75·2	8·1	81·5	5·5	63·5	6·3
14h....	72·0	8·0	79·4	5·5	60·8	6·4
16h....	74·8	8·0	81·4	5·5	61·0	6·4
18h....	82·9	8·1	88·9	5·4	65·6	6·4
20h....	87·2	8·0	85·1	5·4	74·0	6·3
22h....	88·7	7·9	85·9	5·4	79·5	6·3

The relative humidity of the atmosphere, however, undergoes a daily fluctuation and it has sometimes been suggested that by restricting ventilation to the driest parts of the day some real drying could be effected. The kind of diurnal change to be expected is shown by the figures given in Table V which show the mean relative humidity every two hours for the months of October, January and April (which were chosen to be typical of the difficult time of the year) in Kew.

It is at once clear from Table V that the daily change in relative humidity is not due to a change in the water content of the air; in fact, the water content tends to rise slightly as the humidity falls. This indicates that the changes in relative humidity are due solely to corresponding changes in temperature. Thus, it would only be possible to take advantage of the reduced daytime humidity if the temperature of the grain could be correspondingly raised. If the grain were perfectly insulated it is true that its temperature would eventually become equal to the mean daytime air temperature but, since perfect insulation is impossible and since aeration would be confined to about four hours daily, it is unlikely that any real advantage from daytime aeration would accrue.

The Limitations of Forced Ventilation

In the light of the above discussion, it is possible to assess the limitations of forced ventilation as a grain storage technique. Ventilation will certainly prevent heating and, if dry air is used (or, under suitable conditions, warm air) some drying can be effected.

But dry air is not readily available in the British climate, and if dried or warmed air is to be used the process loses some of its essential simplicity.

Simple ventilation with untreated air, therefore, must be regarded primarily as a means of preventing spontaneous heating. This alone is a very useful function and it must certainly prolong the storage life of damp grain. But even if heating is entirely prevented, storage life is not prolonged indefinitely, for the grains remain alive, and at a high water content they continue to age even at low temperatures; hence the germinative power continues to fall in grain kept cool by ventilation, though much less quickly than if the grain were allowed to heat. Also, in spite of forced ventilation, damp grain usually develops a musty smell after a time. This smell may be a serious defect in the grain whether it is wheat intended for milling or barley for malting. It appears, however, that the mustiness developed during ventilation is less permanent than that developed under static conditions, for it is usually quickly removed by turning the grain and continuing ventilation for a few further days.

CHAPTER 6

DRYING GRAIN FOR SAFE STORAGE

It is generally conceded that drying to a "safe" water content is the most effective method of rendering grain safe to store without further trouble. It is certainly true that there are great advantages in bringing the grain to a state in which it needs no special attention or apparatus to preserve it, but it must be remembered that drying is no protection against rodent attack and, unless the water content be taken below 10 per cent. to 11 per cent., most grain insects will be able to live and reproduce. Generally it is not economic to dry grain to a water content so low that all insect activity is inhibited, so that allowance must always be made for the danger of infestation in dried grain.

What is a Safe Water Content ?

Since it is impracticable to avoid all hazards by drying alone, there is evidently no such thing as a truly "safe" water content, but it is easy in the light of experience to state certain water contents below which grain will usually keep free from particular forms of deterioration. Experience, of course, is a guide to the behaviour of grain in the state in which it usually occurs, i.e. with an uneven distribution of water throughout the bulk, but it must be realized that this uneven distribution is itself a cause of deterioration, particularly when the average water content is not far below that at which heating occurs. It is often true to say that the keeping quality of a bulk of grain is no better than that of its dampest part. The suggested safe limits given below, therefore, refer to grain of normal heterogeneity in water content; it might well be that the water content limits could be considerably raised if homogeneity could be assured.

With these reservations the following water contents may be suggested as safe levels in a temperate climate within the limits indicated, but barring always insect, mite and rodent attack.

1. Below 12 per cent. water content, most grain will keep in good condition for perhaps five years. There will be some increase in fat acidity and a few grains will lose viability, but by and large, wheat will be perfectly sound for milling. The loss in viability is unlikely to be sufficient to affect the value of grain for seed (though serious loss in viability tends to set in quickly in wheat after about five years), but would, in most cases spoil barley for malting.

2. About 14 per cent. water content wheat will keep a reasonable quality for milling for eighteen months to two years in spite of increasing fat acidity and falling viability.

3. About 15 per cent. water content wheat should not be kept for more

than nine to twelve months. The longer period is safe if the grain goes into store in early winter, but the shorter period is the limit if several months of summer weather occur immediately after putting into store.

4. About 16 per cent. water content wheat will usually keep in fair condition throughout the winter and into early summer, a total period of about six months. Spontaneous damp grain heating, though uncommon at this water content, can occur, and hence 16 per cent. is not truly safe.

5. Higher water contents than 16 per cent. are definitely not safe, though particular samples may keep fairly well for about six months. Under good conditions, during winter, small bulks of wheat up to 20 per cent. water content quite frequently keep well until spring, provided that the water content is reasonably uniform throughout the bulk.

It usually appears that freshly dried grain keeps better at a particular water content than grain which has not been dried. This may be due to the fact that the heat used in drying partially sterilizes the microflora of the grain, but another factor is probably the intense surface drying which occurs. Since the microflora of grain is either on the surface, or just within the bran, surface drying is particularly effective in killing it, or temporarily inhibiting its growth and metabolism.

The Principles of Grain Drying

It was explained in Chapter 3 that water is lost from grain whenever the water vapour pressure of the surrounding atmosphere is lower than that exerted by the grain itself. If air and grain are at the same temperature, it is true to say that grain will lose water whenever the relative humidity of the surrounding atmosphere is lower than the equilibrium value. But this is not true if the grain is at a temperature different from that of the air. Relatively dry grain will lose water to very damp air if the grain is hot and the air cold. Conversely, damp cold grain will absorb water from hot, dry air so long as the temperature difference persists.

A temperature difference between grain and air blowing over it will not persist for long, for the specific heat of grain is low and the evaporation or condensation of water involves big exchanges of heat. Also, the potentialities of grain as a source of heat are so slight that they may be neglected for this purpose, so that the amount of water which may be evaporated from grain, solely by virtue of a temperature difference between it and the air, depends on the specific heat of the grain.

From this it is clear that there are three general ways in which grain may be dried in a stream of air, ways which differ according to the manner in which heat is used :

1. Air dried without heat and grain not heated.
2. Grain heated but air cold and not dried.
3. Grain cold (at first) but air heated.

These will be dealt with in order.

1. AIR DRIED BUT NO HEAT USED.

Obviously, if some of the water vapour normally contained in air is removed, so as to reduce the relative humidity below that of an atmosphere in equilibrium with the grain, the grain will be dried. But the possibilities of this method are very much limited at ordinary temperatures by the low water carrying capacity of cool air. For example, if air at 50°F. (10°C.) is dried to 30 per cent. relative humidity (it would be difficult to dry large volumes of air to a lower humidity than this), and blown over wheat at the same temperature and 20 per cent. water content (in equilibrium with about 88 per cent. relative humidity), the maximum possible amount of water which could be removed is about 5·41 milligrams per litre of air. This means that in order to lower the water content of the grain by only one per cent., at least 1,500 times its volume of air would need to be blown through. At lower temperatures, the volume of air required would be even greater.

Whatever the conditions, some heat must be supplied to the grain in order to evaporate the water which it contains. If the air and grain are initially at the same temperature, the only source of heat is the incoming air and the grain can only absorb this by becoming cooler. This, in fact, is what happens, and in giving up heat to the cool grain, the air itself is cooled and therefore carries away somewhat less water than the maximum assumed in the above calculations.

Thus, grain drying by means of dried air without any use of heat, though quite a practicable technique, is not a rapid process. It is really a form of drying by forced ventilation.

2. GRAIN HEATED AND DRIED WITH UNHEATED AIR.

This is perhaps the most obvious method of using heat for drying of grain. The conditions are those described in Chapter 5 for phase 1 in the case of hot grain and cool air, i.e. very rapid drying until the grain is cooled. Unfortunately, since grain carries so little heat, cooling is very rapid, so that it is not practicable to remove much water in a single stage by this method.

It is possible to use heat very efficiently by applying it to the grain and not to the air, but only under certain conditions which may not be very convenient or even practicable. The difficulty is that, although much of the heat in the hot grain is used in evaporating water, it is inevitable that some heat must be wasted in merely warming up the air and thus the thermal efficiency cannot reach 100 per cent.

Although single stage drying on this principle is clearly limited in its applications, a thorough study of the process has been made

by Kelly (1941). Kelly found that the greatest quantity of water which he could remove from wheat without exceeding a safe temperature was less than two per cent. He also found that there is for each depth and temperature of wheat an optimum rate of air flow; if this is exceeded too much heat is wasted in warming up the air.

A very popular and successful type of drier is the "radiator" type which is probably most appropriately mentioned at this point. Grain to be dried passes over a series of hot metal surfaces (the radiators) and meets a counter current of unheated air. It is clear that since individual grains are warmed several times by contact with radiator surfaces, and as frequently cooled again by the air stream, this amounts to multi-stage drying on the hot grain–cold air principle. But the air stream is warmed by the heat which it removes from the warm grain (and by contact with the radiators) so that, in the upper stages, hot air is meeting cold grain and the conditions are those of the hot air–cold grain principle.

Before leaving the hot grain–cold air principle, it will be as well to mention a claim which is frequently made for this system. It is claimed that water is removed more quickly when hot grain is ventilated with cold air than when the conditions are reversed. The basis for this claim is largely theoretical; it rests on the fact that when grain is being cooled by a cool air stream there is a falling temperature gradient, and a corresponding water vapour pressure gradient, from the centre to the exterior of each grain. This would be expected to facilitate movement of water through the substance of each grain, but this fact would only be of significance if it could be shown that resistance to this movement is distributed fairly evenly through the grain. If, on the other hand, the resistance to water movement through the grain is concentrated in a thin layer in the bran, the existence of a temperature gradient will have little effect on the rate of drying. In fact the distribution of resistance to water movement in a grain has not been determined but the fact that such resistance is of great importance and that its site is below the surface follows incidentally from the work of Edholm (1932) on intermittent drying, see p. 42.

3. Cold Grain Dried With Hot Air.

Since the immediate effect of passing hot air over cold grain may often be to deposit water, it is perhaps not obvious that this is a practicable arrangement for grain drying. Its success depends on the fact that the incoming air quickly heats up all the grain through which it passes, so that the air stream leaving can carry away much more moisture than the entering stream brings in. Thus, when hot air is used in this way (as in the ordinary drier) it is serving two purposes; it is supplying the heat needed for evaporation of the water and also carrying away the water vapour. Since there is ample heat available, limited only by the supply of air, there is no limit to the amount of drying which can be carried out in a single stage.

In this method of drying, the grain is always cooler than the incoming air (since the air must supply the heat to the grain), and the temperature gradient within the grains rises from the centre to the surface. More important than this, however, is the temperature gradient in the thickness of the mass of grain being dried, for this falls off rather steeply from the point of entry of the air to the point of exit. When relatively high temperatures are being used, as in ordinary grain driers, a steep gradient such as this could be a source of trouble owing to the deposition of water on the grain furthest from the point of entry of the air. This is normally avoided by having a thin layer of grain to be dried (seldom more than six inches and usually less), and a high air velocity. The arrangements are usually such that the air does not nearly reach thermal or humidity equilibrium with the grain, so that evaporation continues throughout the thickness of the layer being dried. This results in inefficient use of heat but makes for very rapid drying.

Temperature Limits for Drying

All grains are very sensitive to heating and this places a limit on the amount of heat which may be applied, but it is by no means easy to specify temperature limits above which a dryer must not operate. There are several reasons why what at first sight appears to be a simple limit to specify is, in fact, very complicated. They have been very clearly set out by Mounfield, Halton, and Simpson (1944), in a paper describing experiments which were designed to investigate what temperatures are actually reached at various stages of a normal drying process.

The Difficulties of Specifying Temperature Limits

Briefly, the problem of specifying maximum safe temperatures in a dryer is as follows:

1. The effect of a particular temperature depends on the water content of the grain. The sensitivity to high temperatures is greatest at high water contents and least in very dry grain; for example, Hutchinson (1944), found that wheat at 3·2 per cent. water content still gave an 80 per cent. germination after being heated to a temperature of 110° C. (270° F.) for an hour, whereas wheat at 24 per cent. water content gave a less germination after heating to only 60° C. (170° F.).

2. The actual temperature of the wheat is always less than that of the hot air blowing over it because the air must be able to transfer heat to the grain to evaporate the water. But the difference in temperature between air and grain decreases as the grain becomes drier and evaporation slower. To some extent, this effect tends to compensate for the greater heat sensitivity of damp grain because, under any conditions of air temperature and flow, the damper grain is, the cooler it is. But the results of Mounfield, Halton, and Simpson

show that the lowering of temperature due to dampness is never sufficient, in an ordinary drier, to compensate for the corresponding increased sensitivity. Their results also show that at any particular moisture content, the grain which starts dampest is hottest because it must have been longer in the hot air stream to reach that water content than a sample which was drier at the start. For both these reasons, it is necessary to use a lower temperature throughout when drying very damp grain than when drying less damp grain.

3. The temperature of grain in a hot air stream depends not only on its water content, but also on the rate of air flow. As the rate of air flow increases, the rate of evaporation of water from the damp grain increases, but not sufficiently rapidly to absorb all the extra heat which the air brings to it. Therefore under otherwise identical conditions, the higher the rate of air flow the higher the temperature of the grain.

4. Damage to grain quality depends not only on the temperature to which it is raised at each particular water content, but also on the duration of the treatment. In a particular case in which damage occurs, it is due to a combination of time and temperature which, in the light of present knowledge, it is usually impossible to analyze. It is, however, always a fact that under otherwise constant conditions, higher air temperatures cause more damage in spite of the fact that they cause more rapid drying and hence shorten the period of exposure to hot air needed for a given amount of drying.

5. A further complicating factor is the inevitable existence of a temperature gradient in the thickness of the grain stream. The grain nearest to the incoming air is always subjected to a more severe treatment than that on the exhaust side, and unless exceedingly thorough arrangements are made for "turnover" of the moving stream, the safe limit is set by the temperature of the most exposed layer.

6. Finally, it must not be forgotten that much exchange of heat will occur between the grain and its surroundings otherwise than through the air stream. Grain will lose heat by radiation and by contact with cool surfaces and, what is more important, will take up heat by the same routes. It may be possible for very damp grain to be heated to a temperature practically equal to that of the hot air without the benefit of any of the cooling effect of drying, simply by contact with hot surfaces which are themselves heated by the air stream.

To summarize: grain passing through a normal hot air dryer reaches temperatures which depend on the hot air temperature, the rate of air flow, the rate of drying, the extent to which gradients are broken by turnover devices, and the amount of contact with hot surfaces. The effect which it suffers depends on its water content at each temperature which it reaches and the rate at which it passes through the inverse processes of heating and drying.

It should also be mentioned that the effect of mild heat treatment may be either beneficial or deleterious to milling wheat from the point of view of baking quality, according to the type of wheat. The general effect of heat treatment is to lower extensibility and increase spring, and this may be an improvement if the former was too high and the latter too low in the original wheat. If the extensibility was low to start with, however, all heat effect is undesirable. This is a further factor making for uncertainty in the results of drying.

Many of the factors mentioned might be standardized for a particular case, but the problem of adjusting treatment with each variation in water content and wheat type is pretty well insuperable. Therefore, any temperature specification which is given and intended to be suitable for application to all types of dryer must allow an ample margin of safety. The extreme precaution would be to specify a maximum hot air temperature equal to the lowest grain temperature which is known to produce damage under any circumstances. But if the chance of grain being heated by contact with hot surfaces without any drying is small, it is safe to allow for a considerable excess of air temperature over grain temperature. Furthermore, although it is impracticable to specify different temperatures for each possible type of dryer, it is quite practicable to vary the specification according to the type of grain being dried or according to the use to which it is to be put.

The hot air maximum temperatures which were specified by the Ministry of Agriculture in 1944 for drying English grain are an example of the type of specification which it is possible to make. The limits were:

Wheat for milling	150° F.
Barley and seed corn up to 24% moisture ...	120° F.
Barley and seed corn damper than 24% moisture...	110° F.
Linseed, mustard, and other oily seeds	115° F.
Oats and dredge corn except for seed	180° F.

It is probable that a dryer could be specially designed to operate with considerably higher temperatures than these without risk, and the use of higher temperatures would considerably increase the throughput of a dryer of given size, but such a machine would probably work in stages and a specification of safe limits would involve a series of temperatures, one for each stage.

Why Specify Air Temperature?

Since the vital temperature is that of the grain and not that of the air it may seem surprising that the limits specified are not those of grain temperature. There are two chief reasons for this. Firstly, it is very difficult, probably impossible in most cases, to measure grain temperature in a dryer while hot air is being blown through it. The volumes of air used in dryers are such that the air never reaches

humidity or thermal equilibrium with the grain and any thermometer bulb placed in the mass will indicate a temperature much closer to that of the air than to that of the grain.

Secondly, the relation between grain and air temperature is changing continually with the progress of drying, and it is only the air temperature which is directly under the control of the operator or of any thermostatic control machine. Thus it would be exceedingly difficult to control grain temperature accurately even if a means of measuring it could be provided.

Drying in Bulk

In Chapter 5 it was pointed out that ventilation with suitably pretreated air (especially warmed air) could be used to effect drying without the use of high temperatures under suitable conditions. The writer has suggested that, if this type of arrangement is to be used with the primary object of drying, some provision should be made for the continual turning of the grain from the bottom to the top of the bin, or to another bin. The object of this is, firstly to remove the driest grain so as to bring grain which is still damp closer to the point of entry of the air (in effect to act as a "turnover" device) and, secondly, to keep grains continually in motion relative to each other and prevent the stagnation of air at the points of contact of the grains.

Another possible method of drying and one which would entirely avoid the application of heat to the grain, would be to mix damp grain with another granular absorbent material in sufficient quantity to absorb all the excess water in the grain. This form of drying by "admixture" has been suggested from time to time (e.g. Moran and Jones, 1945) but the writer does not know of any case in which it has been used on a large scale. It is, of course, used in effect every time that wet and dry wheats are mixed in conditioning bins to temper each other before milling.

Probably the greatest difficulty involved in applying this method is that of finding a suitable absorbing material. The material should be granular, sufficiently different in size from the grain being dried to be immediately separable from it by simple sieving, and cheap.

The advantages of drying by admixture are:

1. No heat need be applied to the grain.
2. It can give immediate protection to grain no matter how damp it is, thus making it possible to deal easily with sudden rushes of damp grain from the field such as would otherwise swamp a dryer.
3. The absorbent material could be dried at leisure in an ordinary drier using very high temperatures.

Against these advantages must be set the following important disadvantages:

1. There are few suitable desiccants (i.e. drying materials) which are cheap, easy to dry, easy to separate from the grain, and not friable.

2. It is difficult to ensure really intimate mixing of two materials of different density (which they probably would be) and of different particle size (which they must be if they are to be separated easily by screening). The process will fail if the mixing is not intimate.

Intermittent Drying

Edholm (1932) has shown that, when grain is dried in a series of short drying periods with relatively long periods of rest between, the amount of water removed per unit of drying time is much greater than when drying is continuous. This is because the limitation to drying rate, once the outer skin of the grain is dry, is the rate at which water diffuses through the grain to the skin. Edholm finds that the gain is greatest when the rest periods are from 1-3 hours and the drying times are about 3-6 minutes. It appears that, if advantage is taken of this principle, considerable savings in heat and power might be made whether drying is effected in the usual rapid way or slowly, in bulk.

The drier designed by Edholm consists of a storage bin traversed at several different levels by layers of air ducts. In each layer, air is blown into alternate ducts and sucked out of the others. Thus, in each layer, air travels horizontally through the grain from one duct to the next. Dry grain is continually removed from the bottom of the bin and damp grain added at the top, the dimensions being so arranged that the grain spends approximately three minutes between the ducts in a stream of air and approximately sixty minutes "resting" between the layers. It thus receives as many intermittent treatments as there are layers.

Obviously a system of this kind could be used as a form of bin ventilation and in a dry climate might be expected to effect considerable drying. It is also clear that this system could be used with dried cool air or with dried warmed air and the savings which could be expected from use of the intermittent principle might be sufficient to pay for the cost of treating the air.

CHAPTER 7

THE SPONTANEOUS HEATING OF STORED GRAIN

The fact that bulk grain sometimes becomes hot, apparently without any obvious cause, is the best known and most widely feared of the hazards to which grain is subject in storage. This phenomenon has already been referred to in Chapter 1, and in later chapters the secondary effect of heating on water distribution in bulks has been described. It is the purpose of the present chapter to examine the causes of spontaneous heating and to study the way in which it develops.

When the grain becomes hot, evidently there must be a source of heat. Grain is known to be a living material, and since all life is accompanied by some liberation of heat, it is natural to suppose that the source of heat is metabolism of the grain itself.

It is possible to test the likelihood of this supposition by calculation from respiration measurements which have been made and using the rate for thermal conductivity of bulk grain given in Chapter 2. The results of various measurements of respiration rate differ widely (a fact which will be commented upon later) but it is reasonable to accept a maximum figure for wheat at a water content below 14 per cent of about 0·16 mg. CO_2 per kg. dry weight per hour (m.k.h.). The heats of oxidation of the principal ultimate substrates of respiration in terms of the amount of carbon dioxide produced are given below :—

Carbohydrate ...	2·6	gram calories per mg. CO_2 produced.
Protein	3·1	,, ,, ,, ,,
Fat	3·4	,, ,, ,, ,,

There is little fat in wheat so that it seems reasonable to assume that the maximum amount of heat which could be liberated by wheat in the course of respiration is about 3·2 gram calories per mg. CO_2 produced. This means that dry wheat will have a maximum heat output of about 1×10^{-7} gram calories per second per cubic centimetre.

The formula given in Chapter 2 (page 8) may be simplified thus :

$$t - t_r = \frac{Q}{6K} . r^2$$

Where t = temperature at the centre of a sphere all parts of which are producing heat.

t_r = temperature at a distance r cm. from the centre.

Q = quantity of heat produced in gram calories per second per cubic centimetre.

K = thermal conductivity in c.g.s. units.

Using this formula it can be shown that the maximum temperature rise, due to grain metabolism alone, at the centre of a sphere of grain four metres in diameter will be about 1·75° C. Such a temperature rise is negligible compared with those which occur during spontaneous

heating. Grain, of course, is not stored in spherical bulks, but for the present purpose, which is to show whether spontaneous heating is likely to occur or not, it is easy enough to guess what size of bulk of more usual shape is thermally equivalent to a sphere. The sphere 4 metres in diameter which is referred to above would be approximately equivalent to a bulk about twelve feet cube. In assessing the thermal equivalence of a bulk it is the minimum dimension which is most important since most heat escapes by the shortest route. It will therefore be realized that grain is seldom stored in bulks which are thermally equivalent to larger spheres than four metres diameter since wheat stored on floors is seldom more than two or three metres deep (and depth is the minimum dimension) and silo bins are seldom wider than four metres.

It is therefore safe to assume that spontaneous heating of wheat, due to the metabolism of the grain alone, will not occur when the water content is 14 per cent. or less. But it is not uncommon for wheat or other grains, as dry as this and even dryer, to heat spontaneously when kept in store for long periods, and in view of the above calculations it is clear that this can only occur when there is another source of heat than that contributed by the grain itself. The writer has made a large number of studies of parcels of dry grain which were heating in various degrees and has concluded that in every case the cause was insect infestation and the source of heat was metabolism of the insects themselves. Many measurements have been made of the respiration rate of various stages of grain insects (some of which are reported in Howe and Oxley, 1944) and calculations similar to that given above have shown that even a very few insects can produce enough heat to cause spontaneous heating.

There are thus two kinds of spontaneous heating of grain, and since they differ in a number of respects it is convenient to refer to them as "dry grain heating" and "damp grain heating." Dry grain heating may be diagnosed by the following features :—

1. The grain water content is in the region of 11 per cent. to 15 per cent.
2. The temperature does not rise anywhere in the bulk above 38 to 42° C. (100° F. to 180° F.).
3. Insects are present.

In connection with (1) above it must be remembered that movement of water as a result of heating and steep temperature gradients may make the surface of the grain very damp. This must be ignored when determining the water content for purposes of diagnosis ; the sample for water content determination should be taken from a point deep in the heating grain. In connection with (2) it must be realized that the temperature at the time of examination may not yet have reached the maximum indicated above, at least not at any point which can conveniently be reached. Diagnosis depends on the fact that the maximum of 108° F. is nowhere *exceeded*. In connection with (3), the discussion of insect development in bulk grain given in Chapter 12 shows that insects may in some cases be very sparse

at the surface in the early stages of heating and may not be easily detected. In nearly all cases, however, sieving a pound or so of grain over a sieve of twelve meshes to the inch will reveal one or two insects in the material passing the sieve.

Damp grain heating may be diagnosed by the following features:

1. The water content of the grain exceeds 15 per cent. In most cases it exceeds 17–18 per cent.
3. The maximum temperature is very likely to exceed 42° C. (108° F.) but will very seldom exceed 62° C. (144° F.) and may quite often remain in the region of 50° to 52° C. (about 125° F.).
3. Insects may or may not be present.

Although the two types of heating are usually distinct, it is not uncommon for features of both to be combined in a single bulk. This can occur when the grain is at a water content near the border line between the two types (i.e. about 15 to 18 per cent.) in the following way. Since the rate of heat production increases with temperature, it is possible for damp grain, potentially capable of spontaneous heating, to remain cool indefinitely if it is sufficiently cool at the start. In this condition, if insect-infestation occurs and develops sufficiently to cause some " dry grain " heating, the respiration rate of the grain may easily rise to a level at which its heat production is sufficient to maintain and increase the temperature. That is to say, dry grain heating initiates, and is superseded by, damp grain heating, with its characteristic higher maximum temperatures.

This change-over from heat caused by insects to " spontaneous " damp grain heating, is only one example of the sensitivity of grain in the border line regions of water content to external sources of heat. It is clear that for each bulk of grain there is a critical temperature which depends on its thermal characteristics, its respiration rate, and the rate of change of the latter with temperature. Below the critical temperature the grain will remain cool and stable, above it the grain will heat spontaneously. It would be very valuable if it were possible to determine for every bulk its critical temperature but, unfortunately, this is a largely theoretical concept for two reasons:

1. The respiration rate changes not only with temperature but also with time, increasing continuously at a rate which itself depends on temperature. Thus the critical temperature is continually falling and the rate of fall is accelerated by a rising temperature.
2. A bulk of grain is seldom homogeneous in respect of either water content or its respiration rate. That is, there are usually damp patches, and these are usually patches of high respiration and heat production. The critical temperature of a bulk must depend on the size and distribution of its damp patches and the stable life of a bulk of damp wheat may depend entirely on that of its dampest portion.

Further consideration of the fact that the respiration rate of stored grain (at least at the border line and higher water contents) increases with time, is of interest. Theoretically, this would be expected to

lead any bulk of damp grain ultimately to break into spontaneous heating eventually. This may be true, but the rate of increase in respiration rate at low temperatures is so low that it is difficult to demonstrate and in fact may not occur. Other forms of deterioration of the bulk, such as invasion by mites or insects, or development of severe musty odours, usually set a limit to the period of storage of dry, cool grain, before spontaneous heating occurs. When grain is kept fairly warm, however, the increase in respiration rate is quite rapid. The increase appears to be neither steady, nor equal in rate for all samples of grain and it may reach a maximum beyond which there is no increase, but it has occurred to some extent in all fresh samples which the writer has investigated from this point of view. In Table VI are given three examples of this increase.

TABLE VI

Increase in Respiration Rate of Damp Wheat after Storage at 25° C. All Respiration Rates Measured over Periods of 24 hours at 25° C.

(Note m.k.h. = mg. CO_2 per kg. dry weight per hour).

Sample No.	Water Content	Respiration Rate	
1603 A	16·70%	On day after threshing	0·199 m.k.h.
		After 14 days at 25° C.	0·937 m.k.h.
1603 B	16·76%	On day after threshing	0·235 m.k.h.
		After 14 days at 25° C.	0·965 m.k.h.
1603 C	17·07%	On day after threshing	0·299 m.k.h.
		After 14 days at 25° C.	1·34 m.k.h.

The increase in rate of respiration which results from storage appears to be irreversible, i.e., the rate does not fall again.

The Cause of Increase in Respiration Rate of Damp Wheat

Progressive, irreversible increase in respiration rate suggests a progressive increase in the amount of respiring tissue. Since the embryo is clearly the most active tissue of dormant grain, the writer attempted to demonstrate an increase either in the size, or in the degree of differentiation, of the embryonic tissue. This was done by removing large numbers of embryos from wheat of high and low respiration (produced by storage at high and low temperatures respectively) rate and comparing them by measurements in various directions and by counting the number of roots and root initials. No significant difference between the embryos could be detected and it was concluded that the increase in respiration rate was not due to any observable change in the wheat embryos.

Studies were also made in the writer's laboratory of the respiration rates of wheat from which the embryos had been removed by insect attack and of wheat from which the skin had been partially removed by abrasion with carborundum powder. These studies, which are reported in Oxley and Jones (1944) and Oxley (1945), showed that in the former case respiration was scarcely affected while in the latter

case it was sharply reduced. The former experiment is confirmed by the findings of Leach (1944) who removed wheat embryos by drilling, and of Lyon (1928) who worked with wheat grains which occurred naturally without embryos. The combined effect of these experiments is to suggest strongly that the major site of respiratory activity in moderately damp wheat is in the bran of the grain and probably mostly in its outer layers, yet microscopical examination of sections of this structure shows few, if any, cells which appear to be actively developing or even living.

It seems an obvious conclusion that micro-organisms on the skin of the grain are chiefly responsible for its apparent respiration. In searching for signs of micro-biological activity the writer made the surprising discovery that most wheat grains have an appreciable development of fungi *underneath* their epidermis. Unless grains are obviously mouldy no fungal hyphae can be found on the *outer* surface of the epidermis although, of course, superficial fungal spores are always present. A similar sub-epidermal fungal mycelium has also been demonstrated under the epidermis of maize (particularly over the embryo and basal parts of the seed) and rye.

The sub-epidermal mycelium is abundant in many samples of English wheat immediately after harvest, when the water content may range from 15 to 25 per cent. or even higher, and is detectable, though in rather small quantity, in Canadian and other wheats with a water content in the region of 12 per cent. The abundance of the mycelium may be a measure of the dampness of grain immediately before harvest.

It is important to note that this sub-epidermal mycelium is quite distinct from fungi previously reported from wheat grains. Previous reports of fungi associated with wheat, and measurements of their amount, have been based on various methods of washing the surface of the grain with sterile water, with or without sand. Such investigations probably reveal only superficial spores which, until they have germinated, can make no measurable contribution to the apparent respiration of the wheat grain. It is true that, if grain is very damp indeed, such superficial spores, which are present in the air and on all materials in varying degrees, will germinate rapidly to produce a fungal mycelium which will be obvious externally and will contribute immensely to the heat production of the grain. But measurements of fungal and bacterial population by surface washing are useless for determining the life in storage of less damp grain (in the region 14 to 18 per cent. water content) because the spores are likely to remain ungerminated for a very long time. The mycelium beneath the epidermis, however, is already developed, and is probably capable of contributing a considerable proportion of the carbon dioxide which appears to come from wheat in the critical water content region of 14 to 18 per cent. It is presumably development of this mycelium during storage which is responsible for the progressive irreversible increase in respiration already described, although the writer has not so far been able to demonstrate such development.

The origin of the sub-epidermal fungi is a matter of some interest, but at present only a speculative answer can be given. It appears that these fungi are quite independent of any external fungi since they occur with equal abundance whether the epidermis is damaged or not; this has been verified by examination of grains which were allowed to fall from the ear when ripe without any mechanical threshing. The epidermis is a continuous layer, one cell thick, which appears to have no stomata or pores of any kind through which fungi could grow from the outside.

The situation of the fungi, growing in the dead tissue of the bran, does not suggest that they are in any way symbiotic with the wheat plant, but proof of this would require further careful investigation. The writer suggests (though he has no experimental evidence for the suggestion) that the sub-epidermal fungi may arise from spores which fall on the stigmata of the wheat flowers in the field. The hyphae which developed from such spores could presumably grow down to the ovules in a similar manner to the development of tubes from the pollen grains. Before ripening of the grain is complete, the situation beneath the epidermis is probably ideal for development of fungi, with a very high humidity, but the process of drying during ripening probably slows fungal growth and may even arrest it altogether so that the mycelium which develops in the field is "fixed" but not killed by ripening.

The full significance of the sub-epidermal micro-flora has yet to be finally settled. If it can be proved that this micro-flora is important in the deterioration of grain, in the water content region between 14 and 18 per cent. (or even damper than this), a number of conclusions follow which may be of practical importance. Although it must be remembered that in the present state of knowledge these are largely speculative it is worth while to list them:—

1. It may be possible to control deterioration of damp grain by the use of fungicidal or fungistatic gases, liquids or solids, as an alternative to drying.
2. Rapid drying may so lower the humidity of the bran that the fungi are enfeebled or even killed. If this is so, grain which has once been partially, but rapidly, dried may be expected to keep much better than grain which has never been dried. In fact this is usually found to be the case (see Chapter 6).
3. It may be found that the keeping quality of damp grain is closely connected with the duration of the later stages of ripening; if these are unduly prolonged, sub-epidermal fungi may be expected to develop to a much greater extent than if drying and ripening are rapid.
4. No amount of scouring or washing of wheat can be expected to improve its keeping quality unless it is sufficiently severe to remove the epidermis. "Peeling" processes, however, might well improve the keeping quality, but since these are always carried out in water they can hardly be regarded as of practical utility in preparation of grain for storage.

CHAPTER 8

METHODS FOR MEASURING TEMPERATURES IN STORED GRAIN

In order to follow the progress of stored grain, or to study its condition at any particular time, it is necessary to make a number of physical, chemical, and biological measurements. The important measurements to make, apart from such things as the physical dimensions of the bulk, are temperature, gaseous composition of the intergranular air (including humidity), and insect infestation. If the levels of these factors are known, the state and future progress of the bulk can be described fairly accurately. In addition, there are a number of factors intrinsic to the grain itself which determine its present state and future progress. The most important of these are: water content, fat acidity, respiration rate, and degree of infestation by micro-organisms. It is the purpose of this and the next chapter to discuss the techniques of measuring the former set of factors, i.e. those which are characteristic of the grain bulk.

Measurement of Temperature in Bulk Grain

Because grain has a low thermal conductivity and a low specific heat, the precise measurement of temperatures is by no means as simple as would appear at first sight. The average thermometer bulb has a considerably higher thermal capacity than that of the grains which it touches, so that if a cold thermometer is put into hot grain the immediate effect is to cool the grain to a greater extent than the thermometer bulb is warmed. Subsequent equilibration requires a flow of heat through the grain from a distance of several inches and this takes considerable time. The thermometer will settle down more quickly if it is moved to and fro so that it comes repeatedly into contact with fresh grains, but if this process is carried out too energetically, there is danger that a false reading will be obtained owing to heat being generated by friction.

If a plain thermometer bulb is slow in reaching a steady state, a thermometer mounted on a large wooden rod with metal protectors is much worse, and usually a mounting such as this is essential if the thermometer is to be sufficiently well protected to withstand being pushed into the grain to considerable depths. The worst type of thermometer, from the point of view of giving low readings, is the short, metal-sheathed type which is intended to be pushed into piles and bags. These have two main shortcomings: firstly, the thermometer is too completely insulated and therefore moves slowly; secondly, the high thermal conductivity of the metal sheath keeps the thermometer bulb in partial thermal contact with the external air. These faults are often aggravated by the fact that such thermometers

are seldom more than a foot long and can, therefore, only give superficial temperatures which are always lower than the maxima and seldom of any significance.

The following data, obtained by plunging an ordinary mercury-in-glass thermometer and a brass sheathed thermometer to a depth of about 8 inches into warm grain, are of interest. The thermometers were previously cooled to about 39° F., and temperature of the grain as determined by a fine wire thermocouple was 76·3° F. The data was obtained with the grain in a one gallon vacuum flask and the room temperature was 68° F.

Time in Minutes	Mercury-in-glass (Unprotected) Degrees Fahrenheit	Brass sheathed mercury-in-glass Degrees Fahrenheit
0	39·2	39·2
1	66·2	44·6
2	68·4	50·0
3	72·0	55·4
4	73·8	59·4
6	74·5	63·1
8	74·8	65·5
10	75·2	67·1
15	75·7	70·0
20	75·9	71·5
25	76·10	72·25
30	76·15	72·80
45	76·25	73·65
60	76·30	74·20
90	76·30	74·30

The unprotected thermometer takes about 12 minutes to come within one degree of the correct result, and is still reading about 0·2° low after twenty-five minutes. The brass sheathed thermometer is still reading 4·05° F. low after twenty-five minutes, and has settled down to a steady reading 2° F. low after an hour and a half. It is clear that in these conditions the sheathed thermometer would never give a correct temperature reading so long as the air temperature is different from that of the grain, owing to the movement of heat to or from the exterior through the brass sheath.

A thermometer mounted in a wooden rod does not suffer from heat conduction to the exterior, but the sheathing, which is very essential for its protection, slows down the movement very much. It is therefore usually safe to assume that the usual type of mounted grain thermometer needs to be left in the grain for at least 30 minutes, often as much as an hour, if it is to give an accurate reading. Such thermometers are best left continuously in the grain and removed only for observation. In the case of stick thermometers, it is probably best that they should be slow moving, as if they are quick to respond

to temperature changes, they will change during the process of removal from the grain and give a reading that is influenced by the temperature of the upper layers. A " stick " is hardly manageable if it is more than 12 feet long, and if temperatures are to be measured at greater depths than this, a rod capable of being screwed together in sections is necessary. With this arrangement, the time required to insert and remove the instrument is so great that the slowest moving thermometer is likely to show a change before it can be examined.

It is probably impracticable to combine in one instrument a good rapidity of equilibration with sufficient robustness to enable it to be inserted to great depths in the grain. The best solution is to have an instrument which measures temperatures at a large number of points simultaneously, and preferably indicates them at a distance without the necessity of removing the instrument from the grain. The most practical means of doing this is by the use of electric thermometers. These will be either resistance thermometers or thermocouples, and it is worth while to consider the advantages and disadvantages of these two types of instrument.

RESISTANCE THERMOMETERS.

This is the type of instrument normally installed in " built-in " temperature-indicating apparatus. They depend for their action on the fact that the resistance of a wire increases slightly as the temperature increases and, since it is possible to measure electrical resistance very accurately, it is possible to obtain accurate measurements of temperature by this means. The advantages of resistance thermometers are :

1. They give " absolute " readings of temperature, i.e., a single electrical measurement gives the absolute temperature of the wire used in the thermometer.
2. They are accurate and constant in calibration.

The disadvantages are :

1. Bad connections in the leads appear as spurious high temperatures ; even very slight extra resistances in the circuit produce substantial errors.
2. They are rather delicate and must always be well sheathed under the conditions met with in bulk grain. They are, therefore, always rather slow moving as fitted to silos and bulk stores.
3. They cannot be made very small.

THERMOCOUPLES.

A thermocouple consists of a circuit composed of two wires of different metals joined in series at their two ends. When the two junctions are at different temperatures, the opposing EMF's which arise from such junctions are unequal, and hence there is an observable EMF in the circuit which depends on the difference in temperature between the junctions. With a suitable choice of metals for the two parts of the circuit, it is possible to arrange for the EMF to be

exactly proportional to the temperature difference over a limited range. For the range of temperatures met with in grain storage (say 20 to 140° F.) a suitable and common choice is copper for one metal and constantan or eureka (an alloy of copper and nickel) for the other.

The advantages of thermocouples are:

1. The single thermojunction which it is necessary to have at the point of temperature measurement is small, quick-changing in temperature, robust, and easily made.
2. If a potentiometer is used for measurement of EMF (i.e., the measurement is made at a null point so that no current flows in the circuit), the resistance of the leads has no effect on the temperature reading obtained, so that bad contacts are unimportant.

The disadvantages are:

1. The reading obtained is not absolute, it is merely a difference in temperature between one junction and another, so that the operator must make two readings (the electrical reading and the reference junction temperature) and add or subtract them.
2. Generally speaking, the apparatus needed for making temperature readings is more complicated to operate than the simple instrument which is used for resistance measurements.
3. There is a possibility of errors due to unevennesses of temperature at terminals and other connecting points which will, in this case, form subsidiary thermocouple circuits.

This comparison of the two systems shows that, whereas resistance thermometers are probably the most suitable instruments for permanent temperature-indicating installations, thermocouples are much to be preferred for temporary and adaptable apparatus. The writer has described thermocouple apparatus suitable for making temperature measurements in grain at any depth (Oxley and Henderson, 1944). Of the two types of apparatus there described, the "thermocouple ropes" have been found to be the more convenient in practice and an account of their construction and use is accordingly given below.

Thermocouple Ropes

Each rope consists of a single eureka wire extending the whole length, and parallel with this are nine copper wires. The copper wires are of different lengths (the longest being as long as the eureka wire) and the end of each is soldered on to the eureka wire, thus making a thermojunction, the lengths of the copper wires being arranged so that the thermojunctions are at convenient intervals. The other ends of the eureka and copper wires are soldered on to the pins of a ten-way connecting plug and finally the whole bundle of wires is covered with two layers of cotton braiding. There is no limit to the number of thermojunctions which can be included in a single rope

but the number nine was chosen as convenient because ten-way connecting plugs were available.

The lengths and arrangements of thermojunctions may be chosen to suit any particular job, but the following suggestions indicate what is useful in practice for normal storage places. For grain stored in bulk on floors the usual arrangement is a rope five metres (16·4 feet) long with thermocouples at the point and at intervals of 25 centimetres (about 10 inches) behind it. This covers a distance of two metres (6·6 feet) which is sufficient for shallow grain, and the close placing of the thermojunctions permits precise study of temperature gradients. For deeper grain, two such ropes may be used inserted at the same point but to depths differing by 2·25 metres, or a rope may be made having junctions at wider intervals. For silos, a rope 33 metres (105 feet) long is usually ample, and in such a case the thermojunctions can be at intervals of three metres (9·8 feet), though this is rather a wide interval. Since most silos which are not already equipped with temperature-measuring apparatus are usually less deep than this, it is often more convenient to have a rope 22 metres (72·2 feet) long with thermojunctions at two-metre intervals.

In order to insert the ropes into the grain, it is necessary to fit the extremity of each with a small metal ferrule which carries a short metal cross piece. This is made to fit loosely into a downwardly-directed hook on one end of a metal rod. The ferrule is attached loosely to the hook, and the rod is pushed down into the grain to the required depth and immediately withdrawn again leaving the rope in position. The metal rod is provided with screwed ends, so that it may be attached to extension rods and pushed to any required depth up to the limit imposed by the resistance of the grain. The temporary presence of a metal rod in grain whose temperature is to be measured naturally upsets temperature distribution for a short time, but it is found in practice that accurate temperature readings may be obtained within 45 minutes from the time of removal of the rod.

The maximum depth to which metal rods with a thermocouple rope attached can be pushed is usually between eight and fifteen metres (26 to 50 feet), and this will not reach the bottom of any but the shallowest of silo bins. In order to fit a temperature rope into a silo bin, therefore, it is necessary to place it in position in the empty bin before grain is run in. If this is done, it is desirable to attach the bottom end of the rope to the bottom of the bin and keep the rope taut as, otherwise, it will be carried out to one side by the incoming grain stream.

These ropes can be exceedingly useful not only for studying in detail the temperature changes in particular bulks of grain, but also for providing temporary "built-in" temperature equipment for any silo or other bins where it is desired to use them. They are very easily used, even in places which are difficult of access, and their use would thus overcome one of the major difficulties which attend adequate supervision of grain stored in improvised granaries or in some old-fashioned warehouses.

A Suitable Potentiometer

Since each thermocouple rope contains thermocouple circuits of different length and resistance, temperature measurements must be made with no current flowing, i.e., a potentiometer null point method must be used. Any potentiometer capable of reading to an accuracy of about plus or minus four microvolts is suitable for this purpose (the thermo-electric power of copper/eureka is about 40 microvolts per degree centigrade), but since the maximum range of temperatures which it is ever necessary to read in bulk grain is about 60° C. (140° F.), the voltage range need only be about 2·4 millivolts. This is very much less than the range usually provided on most commercial potentiometers and enables design of a very simple and convenient instrument specially for grain temperature measurements.

Owing to the low voltage range, the bridge wire may conveniently be of copper; thermo-electric errors are avoided by use of a copper contacting chisel. Owing to the low resistance of the bridge wire, the potential drop across it may be read directly (or after multiplication by a suitable copper extension resistance) on a millivoltmeter, and this may be adjusted to a value such that a scale previously marked on the bridge reads directly in degrees Fahrenheit or centigrade as desired. A portable mirror galvanometer with low coil resistance can be incorporated for indication of the null point, and a selector switch can be fitted to select which temperature point it is desired to read. The reference junction should be embedded in a block of brass, together with the bulb of a thermometer, and insulated by a wooden or cork sheath to prevent rapid temperature changes.

With this instrument, a series of nine temperatures given by a single thermocouple rope can be read easily in two to three minutes, and one instrument can therefore be used in conjunction with many ropes.

CHAPTER 9

MEASUREMENT OF CARBON DIOXIDE AND WATER VAPOUR IN THE INTERGRANULAR ATMOSPHERE

The intergranular atmosphere in bulk grain consists of ordinary air more or less modified by the activities of the grain and its pests. The modification consists in depletion of oxygen, production of carbon dioxide and production or depletion of water vapour; nitrogen remains unchanged. The amount of oxygen depletion is usually very close to the amount of carbon dioxide production and, since it is more difficult to measure oxygen than carbon dioxide, it is usual to measure only the latter.

As pointed out in Chapter 2, there is often a close relation between carbon dioxide concentration in the inter-granular atmosphere and the grain temperature, but this applies only when the grain is quite warm, and apart from such cases, there are occasions when grain is potentially unstable in temperature but is not yet appreciably warm. Such a state may be indicated by an abnormally high carbon dioxide concentration.

Sampling of the Intergranular Atmosphere

The writer knows of no apparatus sufficiently simple and robust to be capable of being pushed down into grain to measure carbon dioxide concentrations on the spot. It is necessary, therefore, to take samples of the intergranular atmosphere by means of a tube inserted to the appropriate point. In many cases, no sharp changes in carbon dioxide concentration from place to place will be expected and a few infrequent samples will be adequate, but there will be some occasions (as when a zone of carbon dioxide production is being sought, or the direction of air circulation studied) when it is necessary to take samples from points within a foot or two of each other. In this event, it is important that the amount of air withdrawn from each sampling point shall be as small as possible and this requires not only that the samples shall be small, but also that the cross sectional area of the sampling tube shall be the least which is compatible with a reasonably low air friction. The necessity for a small cross sectional area arises because the air standing in the tube must be swept clear by a preliminary draw-through before sampling, and if the tube is large, the quantity of air required may easily exceed the size of the sample.

In practice, equipment of the following type has been found suitable for sampling the intergranular atmosphere for carbon dioxide determinations. The sampling tube is of steel or lead. The former, though everlasting, is inconveniently stiff and awkward to straighten; lead is very convenient and easy to handle, but will not withstand

frequent usage and is not even strong enough to be withdrawn from grain more than 20 to 30 feet deep unless it is reinforced with a steel wire rope. The internal diameter of the tube is about 0·7 to 0·8 millimetres which gives a total volume of between 0·4 and 0·5 cubic centimetres per metre length (one cubic inch in 35 to 45 yards), so that a preliminary draw-through need not exceed 2·0 c.c. on a 35 metre length. In view of the small diameter of the tube, it is necessary to fit a filter at the point in order to prevent the entry of grain dust. This takes the form of a cotton wool plug, contained in a short length of three-sixteenths-inch diameter brass tube, which forms a ferrule similar to that used on the temperature ropes by which the tube is temporarily attached to screwed iron rods for insertion into the grain.

The samples are most conveniently drawn into evacuated glass bottles up to 100 c.c. capacity. These may be evacuated by a portable pump immediately before use (which avoids errors due to leaks), and a supplementary supply of smaller ones may be used for the preliminary draw-through. The latter are only necessary, however, if it is important to keep the size of the draw-through to a minimum and constant in volume, as when samples are being taken very close together. Otherwise, the mouth may be used to suck through a small quantity of air.

The samples having been taken, the amount of carbon dioxide they contain is best measured either by a gasometric method, or by means of a catharometer. Since the determination of carbon dioxide concentrations is an essential part of the method of measurement of insect infestation described in the next chapter, it will be worth while considering here suitable forms of gasometric apparatus and catharometer.

A Gasometric Method of Determination of Carbon Dioxide

The writer has described elsewhere a very convenient form of gasometric apparatus (Oxley, 1944 a.), and readers are referred to the original description for a full account of the construction and sources of error. The apparatus is best made to work with a small sample, say 5 c.c. In this case, it will consist of a vertical tube of 5 c.c. capacity expanded into a bulb at its upper end and with a parallel bore graduated section covering a range of one cubic centimetre below. The bottom end of this tube is connected to a large diameter rubber tube full of mercury which can be compressed under a hinged wooden flap, thus filling the graduated tube. This flap can be moved freely by hand or adjusted accurately by screw. At its upper end, the 5 c.c. tube is attached to a three-way glass tap which places it in communication with either a short tube for intake of samples (position A), or with a U tube containing potassium hydroxide solution (position B). The latter tube has a narrow bore limb connected to the three-way tap and a wide bore limb which can be closed at its upper end. The narrow bore limb has a single line engraved on it, and the amount of potassium hydroxide solution is adjusted so that its surface level is near to this line. The whole apparatus, except the rubber mercury

tube and its flap, should be enclosed in a glass water jacket to even out temperature fluctuations.

The method of use is as follows: With the tap turned to position A, the flap is closed until the graduated tube and short sample intake tube are full of mercury. A sample bottle, or a glass syringe as used in the procedure described in Chapter 10, is connected to the sample-intake tube and a sample is drawn in by lowering the mercury to near the 5 c.c. mark. The tap is turned to position B and the mercury level adjusted to bring the potassium hydroxide solution level exactly to the engraved line. The volume of the air sample is then read on the graduated tube. The carbon dioxide is now absorbed by compressing the flap and driving most of the sample into the potassium hydroxide U tube. Since the whole sample cannot be brought into contact with the potassium hydroxide solution (which absorbs the carbon dioxide) on any one occasion, the flap is compressed and released about twenty times, and during this process, the last traces of carbon dioxide are removed. The mercury is now carefully readjusted so as to bring the solution level back to the engraved line on the U tube, and the new reduced volume of the sample is read on the graduated tube. The reduction in volume is equal to the volume of carbon dioxide originally contained in the sample, and this may be expressed as a percentage of the original volume.

Two sources of error must be considered. Any change in temperature or atmospheric pressure between the first and second readings of the sample volume will produce changes indistinguishable from carbon dioxide absorption. When this apparatus was originally described, it was proposed to close the wide limb of the potassium hydroxide U tube so that the air contained above the solution could act as a compensator for temperature changes. This may be done if desired, but in practice it is found that determinations may be made so quickly that no substantial changes ever occur, provided that the operation is carried out in a room of reasonably equable temperature.

The second source of error is that due to water vapour exchanges between the sample and the potassium hydroxide solution. A table for computing this error is given in the writer's original description, but usually the error may be kept to a negligible amount if the solution of potassium hydroxide is made of such a strength that its water vapour pressure is equal to that of the average intergranular atmosphere. For this purpose, a solution in equilibrium with 70 per cent. relative humidity is usually suitable, though a higher humidity (say 80 per cent.) should be used if samples are taken from damp or hot grain.

The strengths of these two solutions are: Seventy per cent. relative humidity: 25 gm. potassium hydroxide per 100 c.c. water, specific gravity 1·238 at 15° C. Eighty-five per cent. relative humidity: 15·75 gm. potassium hydroxide per 100 c.c. water, specific gravity 1·147 at 15° C.

The Catharometer

The catharometer is an electrical instrument for determining the concentration of various gases. In the present book, it is only necessary to describe the principle of the apparatus; the construction is very specialized and can be carried out only by a suitable instrument-making firm. In this instrument, two identical platinum wires are mounted similarly in similar glass tubes and heated by an electric current which passes through them in series. The temperature which the wires reach depends on the ability of the gas surrounding them to remove heat, so that if they are surrounded by identical gases, their temperatures, and also their electrical resistances, will be equal. If the gases differ only in one constituent, the effect of this constituent in removing heat from the wire is thus reflected directly, in its resistance and can be indicated directly on a meter which records the out-of-balance current of a Wheatstone bridge, two of whose arms are the platinum wires.

One wire is sealed permanently with dry air and the other is surrounded by the dried, unknown gas sample. Since water vapour has been removed from the gas surrounding both wires, it may be assumed that the sample differs from the standard only in having carbon dioxide in it. It is possible to calibrate the indicating instrument directly in percentage of carbon dioxide, and in this way, it can be made exceedingly simple to operate. It usually requires about two minutes for the wires to reach steady temperatures and for the instrument to give a steady reading.

Measurement of Intergranular Humidity

From time to time, attempts have been made to devise an instrument capable of being pushed into grain which would indicate, preferably at a distance, the relative humidity of the grain atmosphere An instrument depending on a suitably prepared hair was, for example, designed by Pap (1934), and the writer and his colleagues have experimented with an instrument using wet and dry thermocouples, but no completely satisfactory instrument has yet been devised. The major objection to all instruments so far proposed, is that they have a considerable thermal capacity and, therefore, do not quickly come into temperature equilibrium with the grain. So long as there is a temperature difference between grain and instrument, a correct reading cannot be obtained. This means that an intergranular hygrometer must be left as long in position as it would be necessary to leave a thermometer before it gives a steady reading. But humidity, unlike temperature, is not likely to change appreciably with time in a grain bulk, so that a hygrometer, permanently in position, would not be a useful instrument. What is needed is an instrument capable of giving a rapid and accurate reading on being pushed into grain in various places; if such an instrument ever becomes available it is possible that humidity measurement may ultimately replace water content determination as a standard on which to base judgements of keeping quality of grain.

In the absence of a meter reading directly in humidity, the best alternative is to take small grain samples from the points to be investigated and either determine their equilibrium humidity directly, or infer it from the water content. If the relative humidity equilibrium is to be determined directly, a suitable method is to seal the sample in a small container with a calibrated paper or hair hygrometer or with one of the humidity-sensitive cobalt thiocyanate papers described by Solomon (1945). For either purpose, very small grain samples are sufficient, and it is very convenient to have a spear which will take samples of about one ounce. The advantages of such a spear are its convenience for handling and the ease with which it may be pushed into the grain, even to depths of twenty or more feet. A suitable design for such a spear is given by Oxley and Henderson (1944), and it is there suggested that 6 inch by $\frac{5}{8}$ inch hard glass test tubes are very suitable containers for taking such samples to the laboratory for determination of water content or humidity.

The writer has frequently been asked why it is not practicable to determine the amount of water vapour contained in gas samples taken through a capillary tube in the same way as described above for carbon dioxide. It is argued that such data (i.e. absolute humidity) could be converted easily to relative humidity figures.

The main objection to this proposal is that there is always some adsorption of water on the metal surfaces of a tube through which a sample is drawn, and if the volume of air drawn through is small in relation to the internal surface of the tube, this can be an exceedingly serious source of error.

Secondly, if the sampling point is at a higher temperature than the upper layers of grain, there is danger that the air humidity will pass the dew point on being cooled and deposit a considerable part of its water vapour as liquid in the tube.

Thirdly, the absolute humidity can only be converted to relative humidity if the temperature is known, and it might not be convenient to determine temperature at exactly the same points as are chosen for gas sampling. Admittedly, temperature also affects the relative humidity equilibrium of grain samples, but this effect is slight and is not sufficient to affect the order of the answer obtained, whereas the exact temperature must be known if the conversion from absolute to relative humidity is to be sufficiently accurate to be of any use at all.

CHAPTER 10

MEASUREMENT OF INSECT INFESTATION BY CARBON DIOXIDE PRODUCTION

Various features of insect infestation in grain are dealt with in later chapters, and the purpose of the present chapter is, therefore, not to consider the biology or physical relationships of insects, but to explain in detail a method, known as the "carbon dioxide method," for measuring insect infestation. For this purpose, insect infestation may be regarded as analogous to the physical and other characteristics of particular bulks of grain which it is necessary to measure, in order to assess their potential keeping quality.

It may be stated at once that no method is available for measuring insect infestation *in situ*; it is always necessary to withdraw samples from the bulk. While the small one-ounce sampling spear referred to in Chapter 9 (p. 59) in connection with water content sampling may be used also for taking samples for determination of insect infestation, it is really rather too small for the job. Usually, the smallest sample which it is worth while using for measurement of insect infestation is about four ounces, and even this can only be taken to represent the immediate vicinity of the sampling point; a sample to represent the whole of a bulk cannot be less than two or three pounds, even if the most careful methods of dividing and compositing are used.

The method to be described below provides a means for expressing, in one figure, the amount of insect infestation in a sample, but the extent to which this may be used to characterize a whole bulk depends solely on the extent to which the sample is representative.

This method depends on the fact that, although insects are never more than a very small fraction of the total weight of a grain sample, they contribute a very large proportion of the total carbon dioxide which the sample produces. This is because grain, although living, is a resting stage of the plant and its metabolism is exceedingly low. Insects, on the other hand, are very active and their metabolism is very high for their weight.

This is best illustrated by reference to a typical infested sample of wheat. This contained ten weevils in a pound, many of them larvae and therefore not visible. The weight of insects totalled 25 milligrams and the weight of grain was 454,000 milligrams, but the carbon dioxide production of the ten insects was about seven times that of the wheat. Thus, in this typical example, the insects were producing about 130,000 times as much carbon dioxide as an equal weight of grain.

The carbon dioxide production of wheat is never zero but, if the wheat is dry, it is so low that usually it may be neglected. If it is not so low that it can be neglected, it is at least certain that the dampest wheat which is ever likely to be shipped in bulk will give a carbon dioxide production for which it will be easy to make allowance.

British experience suggests that this may not always be true for imported maize, some of which may have a fairly high carbon dioxide production, even in the absence of insects, but if water content determinations are made as routine, the operator will always be warned of such damp material.

A point in favour of this method is the fact that if grain gives a high carbon dioxide figure, this, in itself, indicates that the grain is unfit for storage. It is true, without exception, that a high carbon dioxide figure indicates poor keeping quality and a proneness to spontaneous heating, whether from insect infestation or other causes.

Determination of the Carbon Dioxide Figure

The technique of this method is very much simplified by making use of the fact that the volume of intergranular air in any container completely filled with grain is practically constant, and characteristic of the type of grain. A full table of intergranular space percentages is given by Jones (1943), and from these data it can be seen that wheat, rye, rice and maize (i.e., the naked grains) are very similar in this respect, having an intergranular volume of between 38 and 41 per cent. (" uncorrected values ") when tightly packed into bottles of about half pint size or larger.

Within the limits of accuracy of this method, it is reasonable to assume that all the naked grains have the same intergranular air volume. Hence it is possible to express the carbon dioxide production in terms of the concentration produced in the intergranular atmosphere in a given time. This is very much simpler than measuring the total quantity of gas produced by a certain quantity of grain, for it avoids the necessity for weighing or measuring the sample, or for removing the whole of the intergranular air for analysis. The procedure for determination of the carbon dioxide figure of a grain sample thus consists essentially of three steps, as follows:

1. Grain to be tested is placed in an airtight container, which it must completely fill.
2. The grain is then incubated at a standard temperature for a standard time.
3. The concentration of carbon dioxide in the interstitial air is estimated. This concentration is the " carbon dioxide figure."

Apparatus Required

(*a*) Airtight Containers for Grain.—The containers may be of any size that can be filled conveniently. Glass bottles of 500 c.c. (16 fl. oz.) capacity have been found to be suitable. The bottles are best closed with rubber stoppers; screw-topped bottles are unsatisfactory as it is difficult to make them air-tight and grains are apt to get under the washers. A tube of small bore (about 1-2 mm.) for withdrawing the air sample must be provided. The tube must be

closed during the incubation, and should be fitted with a glass stop-cock for this purpose, although a short length of rubber tube with a clip may be used. Much larger containers, such as petrol cans, may be used if sufficiently large samples are available and with these larger syringes may be used and the whole process made more crude without loss of precision.

(*b*) INCUBATOR.—Temperature control should be within the range plus or minus 1° C. (1·8° F.) at 25° C. (77° F.).

(*c*) SYRINGES.—A syringe should be used for withdrawing a portion of the interstitial air from the incubation bottle for analysis. It must be completely airtight, and should hold sufficient air for two analyses by whatever apparatus is available. All-glass syringes of 20 c.c. (two-thirds fluid ounce) are convenient; they should be lubricated with medicinal liquid paraffin oil.

(*d*) GAS ANALYSIS APPARATUS.—A gasometric method is appropriate, as it is required to measure a concentration of carbon dioxide and not an absolute quantity, and the accuracy of such methods is of the required order (about plus or minus 0·2 per cent. CO_2). A catharometer is ideal if large numbers of samples have to be dealt with, but is likely to be too elaborate and expensive if only small numbers of samples are examined daily. Both types of apparatus were described in Chapter 9.

Procedure

(*a*) SIEVING.—A sample may be sieved when received, in order to remove free-living insects. These may then be counted while a carbon dioxide determination is made on the sieved sample. The accuracy of interpretation of the results is thus increased, since the carbon dioxide method is used only to measure the insect population not removed by sieving. Sieving and counting, however, are tedious processes and, if an estimate of total life is all that is required, as will normally be the case, sieving may be omitted, and all insects in the sample may then be included in the incubation bottle.

(*b*) PRE-INCUBATION.—Interpretation of the carbon dioxide figure is made more reliable if, before grain samples are sealed up for incubation, they are kept for any convenient period up to 24 hours at 25° C., in order to acclimatize the insects to the unusually high temperature. This is more important when the grain bulk is cold. During the pre-incubation period, the samples must not be sealed up; they should be submitted to this treatment in small bags, wide-mouthed jars with open tops, trays, or open tins, covered with muslin to prevent the escape of free-living insects.

(*c*) AIRING.—At the beginning of incubation, it is important to ensure that no carbon dioxide is sealed up with the grain sample. There may be carbon dioxide in the air within or between the grains, or in the air in the bottle. If the grain sample has been kept in a bag,

it is probably already sufficiently aired, but if it has been in a tin or air-tight bottle (this is undesirable since it may affect the vitality of the insects) an airing is essential. This is also necessary if the sample has been withdrawn only a few minutes previously from the main bulk of grain, since the atmosphere in the bulk may well contain an appreciable concentration of carbon dioxide, some of which will be retained within the grains. Each sample should therefore be aired as a matter of routine by being spread thinly on a tray or sheet of paper for about fifteen to thirty minutes before bottling up. Bottles which have not been open to the air during the previous few hours should be aired by blowing air into them, or evacuating them and refilling with room air.

(*d*) Water Content.—Wherever possible, it is advisable to determine the water content of the grain, since the carbon dioxide output of clean grain varies with water content. If this is to be done, the sample for water determination should be taken immediately before bottling for incubation. Water content is unimportant below about 15 per cent., and if it is certain that the grain does not exceed this dampness, a determination need not be made. At this stage also, it is well to note whether the grain is visibly mouldy, as such grain cannot be tested effectively for insect infestation by the carbon dioxide method.

(*e*) Filling the Bottles.—Bottles must be dry before they are filled. To ensure constancy of packing, and hence of intergranular air space, fill the bottle, shake down by tapping a few times on the table, and make up the level with a few more grains. The stopper may then be put in place and pushed well down until it is firmly in contact with the grain in the bottle. Close the capillary tube by the stop-cock or clip.

(*f*) Incubation.—The normal conditions for incubation are 24 hours at 25° C. (77° F.). If other periods are used, the carbon dioxide figure must be modified accordingly, as explained later. If large bottles are used, time should be allowed for heat to penetrate the mass of grain. For the case or ordinary glass bottles approximately cylindrical in shape, the following empirical rule has been found to give, with sufficient accuracy, the extra time which is necessary for warming up when grain, originally at a temperature between 10° C. and 15° C., is incubated at 25° C. :—

$$t = d^2 - 50$$

where t = extra incubation time in minutes
d = external diameter of the bottle in centimetres.

The correction may be neglected if the extra time which is found to be necessary is less than half an hour as it is for all ordinary bottles up to 500 c.c. capacity.

(*g*) Removal of Air for Analysis.—Expel all air from the syringe, connect it by a short rubber tube to the bottle, open the stop-cock

or clip, and draw air into the syringe. In order to mix the small amount of room air which is present in the rubber tube with the air in the bottle so that it introduces a negligible error, the piston of the syringe should be moved back and forward several times and finally the stop-cock closed while the piston is held out to its full extent. When the piston is released, it will move inwards until the air in the syringe is at atmospheric pressure. Close the rubber tube with a clip before disconnecting the syringe from the bottle.

(*h*) ANALYSIS OF THE AIR SAMPLE.—With a gasometric method, duplicate determinations of carbon dioxide should usually be made in order to get sufficient accuracy, but this should not be necessary with a catharometer. The room air in the rubber tube must be well mixed with the gas sample in the analysis apparatus to reduce the error it causes.

Corrections

The carbon dioxide figure thus obtained needs no correction if standard conditions were used, namely, the temperature of incubation was 25° C. (77° F.), the period 24 hours, and the grain tested was wheat, peas, split peas, haricot beans, polished rice, or a similar small, naked grain. If the conditions used were non-standard, it is possible to make some corrections to obtain a standard carbon dioxide figure.

No regular correction can be given for temperature, since the effects of temperature changes are different for different insects. The majority of grain insects, however (with some exceptions), are below their sustained respiration optimum at 25° C., and thus a temperature a few degrees higher will usually give a considerably higher carbon dioxide figure than standard. Similarly, a lower temperature will usually give a lower than standard figure. Thus, although it will be possible usually to say in which direction a figure obtained at a non-standard temperature is in error, it is impossible to say by how much. It is desirable to make every effort to use the standard temperature.

A correction for non-standard time may be made by direct proportion. This involves dividing the uncorrected figure by the number of hours actually used for incubation and multiplying by 24. This method of correction is quite accurate, provided that excessively short periods (e.g., six hours or less) are not used. Also, it must be noted that the accumulation of carbon dioxide reduces the rate at which insects produce the gas. This effect becomes pronounced when the concentration exceeds about 8 to 10 per cent., and hence, if the uncorrected carbon dioxide figure exceeds this level it is not possible to correct it.

A correction for the effects of variations in the intergranular air space is given in the table below which is calculated from the data of Jones (1943). For some other, less common, commodities, Jones's paper should be consulted :—

Linseed	multiply CO_2 figure by 0·9
Small yellow maize	,, ,, ,, ,, 1·1
White " horse tooth " maize	,, ,, ,, ,, 1·2
Fine oatmeal	,, ,, ,, ,, 1·2
Barley	,, ,, ,, ,, 1·3
Wholemeal flour	,, ,, ,, ,, 1·3
Oats	,, ,, ,, ,, 1·4
White flour	,, ,, ,, ,, 1·4
Wheat germ	,, ,, ,, ,, 1·5
Rolled oats	,, ,, ,, ,, 1·6
Wheatfeed	,, ,, ,, ,, 1·7

What the Carbon Dioxide Figure Signifies

If the water content of the grain sample has not been determined and there is doubt whether grain is, or is not, damp, it is necessary to assume that a carbon dioxide figure up to 0·3 per cent. may represent insect free grain. If, however, the grain is known to have a water content less than 14 per cent., a carbon dioxide figure as high as 0·3 per cent. must be regarded as strong evidence of a slight insect infestation.

A result between 0·3 per cent. and 0·5 per cent. indicates either a slight insect infestation or a water content higher than 15 per cent., and grain giving such a result is probably not suitable for storage beyond a few more months. Grain that gives a result between 0·5 per cent. and 1 per cent. should be kept under close observation and the test repeated at fortnightly intervals; it is certainly not suitable for prolonged storage. If the carbon dioxide figure exceeds 1 per cent., it is certain that a potentially dangerous insect infestation is present and control measures should be adopted without delay.

It is possible to estimate from the carbon dioxide figure the numbers of certain insects which are present. The precision of the estimate depends upon the information which is available concerning the sample. At the best, this will be limited usually to an indication of the species of insect present (obtained by sieving the sample as described above) and the water content of the grain. If only a few species are present and the water content of the grain is low, the following data may be used for making such an estimate :—

In a sieved sample of grain, a 1 per cent. carbon dioxide figure indicates an infestation of approximately 33 weevils (*Calandra spp.*) larvae per pound, assuming that each stage of larva is present in numbers proportional to its duration. This implies that egg laying has proceeded at a constant rate up to the time of sampling. If there is reason to think that older stages predominate, a lower infestation than this is indicated, while if young stages predominate, the infestation is higher. The same standard may be used for an unsieved

sample (i.e., one which includes adults), with some approximation to accuracy, because the carbon dioxide production of adult weevils is not greatly different from that of mixed pre-adult stages.

The above relates only to true grain weevils or rice weevils; the relation between population numbers and carbon dioxide production of other insects is rather less well known. Approximate data were given by Howe and Oxley for a number of other insects, but some of these are now known to be somewhat inaccurate. It is probably not very useful to attempt to convert carbon dioxide figures to insect numbers; it is better to use the carbon dioxide figure as a measure of grain quality and by experience to build up a series of standards by which to judge the potential keeping quality of the grains in much the same way as water content is at present used.

CHAPTER 11

INSECT INFESTATIONS IN BULK GRAIN

Insects cannot arise, except from other insects. The idea of "spontaneous generation" of organisms has been for so long discredited, that it is surprising to find that it persists in some quarters for the particular case of grain. In other words, there are still some people who think it possible that when insects or mites appear in grain that they may have been generated by the grain.

It is most important that this idea should be squashed, not only because it is utterly incorrect, but also because from the concept of spontaneous generation it follows that hygienic measures designed to isolate clean grain from possible infection are either useless or at least only partially useful. In fact, such measures are, in many cases, the cheapest and best means which can be operated to keep grain free from insect infestation and, if suitable buildings and machinery are available for rigorous isolation of all infestations, grain can be kept completely free from insects for many years without the use of any fumigants, sprays or dusts.

Such rigorous separation of infestation from clean grain, however, can seldom be operated and, in any case, the majority of those who handle grain receive it from other parties over whose action they may have no control.

It rarely happens that grain is under the same control from the time of harvest to the time of milling, so that there is seldom any possibility of applying strict hygienic measures throughout the history of each grain parcel. This is particularly true of imported grain, and as much which is imported to Britain comes from warmer climates, where insect infestations are more rife than at home, it naturally happens that some kinds of imported grain present a serious insect problem directly they are received.

Thus, however strictly he may apply hygienic measures within the area under his direct control, no operator who handles grain can be sure that he will never be obliged to deal with insect infestations. In fact, most millers and others who store grain are from time to time confronted with insect problems which must be dealt with in some way.

It is the purpose of this and the remaining chapters to deal with the more important biological principles involved in insect infestations of grain.

The Life History of Insects

The young of most insects are not only smaller than the adults but also very different in appearance. Typically, an insect egg hatches to produce a larva or grub which is a worm-like, segmented,

animal with usually six minute legs at its front end. A caterpillar is a larva, and although not all insect larvae are of exactly this form, it is a familiar example which may be carried in mind.

The larva of an insect eats vigorously and grows rapidly, but as it has a skin which stretches very little and grows not at all, the growth of the larva proceeds by a remarkable series of jumps. When the skin is stretched to its limit, the larva ceases to eat, and after a short time the skin splits. The larva crawls out of its old skin and is then seen to have a new soft skin beneath; this process is known as "moulting" or "ecdysis." The new skin is larger than the old, and while still soft and fresh it will stretch to allow for growth. Usually, also, the new skin has folds and creases which can be straightened out to permit enlargement of the larva. The larva, therefore, grows rapidly for a short time after every moult, but the new skin soon hardens and, being stretched to its limit, growth ceases until the next moult.

As the larva grows, it not only increases in size but also changes slightly at each moult to become more like an adult. These changes, together with the changes in size, result in each stage of the larval life often being quite clearly recognizable, and it is common to refer to the first, second, third, etc., larval stage with quite a definite meaning for some insects. Other insects, however, moult a variable number of times in their life and the changes accompanying each moult are not definite.

Some insects change gradually in form throughout their larval life until they become adults with no particularly big change in form at any stage. Examples of such insects are silver-fish and earwigs. Most of the more highly evolved insects, such as beetles, butterflies, and moths, however, accomplish the greater part of their change from larva to adult in a single jump. This is a most remarkable change; it occurs by formation of a stage called the pupa at the end of larval life. The typical pupa has a very thick skin and no legs, eyes, or mouth; its movements are usually limited to the ability to move slightly its jointed hind end. Inside the pupal skin, the larva is largely broken down and dissolved into a more or less disorganized mass of cells, and out of this mass of cells is gradually formed a new complete adult insect with wings (in the vast majority of insects) six legs, a separate head, thorax, and abdomen, and a pair of antennae and two large eyes on the head.

The adult insect does not grow and, therefore, does not moult and has very little need to eat. Some adult insects, in fact, do not eat at all, but the majority eat a little (particularly females if they lay very many eggs), and many drink if given the opportunity. The adult eventually dies of old age if not previously killed by a predatory enemy or disease, and the race is carried on by the eggs.

Thus, the life history of an insect is fundamentally different from that of other animals, and it is worth repeating and emphasizing the main differences.

1. The insect usually has four clearly distinct stages in life:
   (*a*) The egg,
   (*b*) The larva,
   (*c*) The pupa,
   (*d*) The adult.

2. The larva eats voraciously and grows in a series of jumps, moulting its skin at each jump.

3. The pupa is almost immobile and neither eats nor grows.

4. The adult is sexually mature and the females lay eggs. It can move rapidly and many can fly, but it does not grow or moult and it usually eats relatively little.

Development of Insects in Bulk Grain

The development of an insect infestation in the special conditions of bulk grain follows lines somewhat different from those of insects living freely in a warehouse. The dominating features of a bulk of grain which are responsible for the special type of infestation which develops are the physical characteristics which were described in detail in earlier chapters. Particularly the low thermal conductivity, the large size and the closely controlled intergranular humidity are very important features of the bulk grain environment.

In temperate climates, mean air temperatures are normally well below the optima for development of most grain insects, for most of them are of tropical or sub-tropical origin. Temperatures low enough to kill the insects are fairly frequent, but temperatures above the optima are rare. This fact is important, for it means that if grain becomes warmer than the average air temperatures, it is to the advantage of the insects, whereas in much hotter climates, an increase in temperature above the average might be to the disadvantage of the insects.

In the course of development in bulk grain, an insect infestation changes the environment in three chief ways:

1. Heat is produced.
2. Humidity is changed: (*a*) by redistribution of water in the bulk as a result of heating, and (*b*) by production of water by the insects as a result of oxidation of hydrogen in their food.
3. The composition of the intergranular atmosphere is changed by production of carbon dioxide and consumption of oxygen.

The way in which changes of this kind occur in bulk grain having been already explained in earlier chapters, we may now proceed to consider the probable progress of an infestation in bulk grain. The discussion which follows (based on Oxley and Howe, 1944) relates particularly to grain weevils (species of *Calandra*) and, except where otherwise stated, all figures given relate to these insects.

Suppose that a small number of adult insects are present within a bulk of otherwise clean grain, and at least eighteen inches from the

surface of the bulk. If the temperature of the grain is above the minimum for egg laying (i.e. about 12° C. = 53·5° F.), eggs will be laid. If the temperature is below the minimum for egg laying, but not too low, adults of most insects are able to survive for several months without ageing appreciably and will be able to lay eggs when the temperature becomes suitable.

If the temperature of the grain is below 20° C. (68° F.) development of most insect pests will be very slow indeed, and weevils may take 120 days to complete their life cycle at the relative humidity usual in dry wheats, i.e., around 60 per cent. In grain damper than usual, periods down to sixty days may be expected.

Temperatures higher than 20° C. (68° F.) are not normally maintained in this country for more than a few months each year and hence it is quite possible for the first generation of weevils to be interrupted by the onset of winter before it is complete. This is probably the most serious hazard which besets the precarious early stages of an infestation.

In winter, temperatures near freezing will be reached usually by January or February throughout all but the largest bulks of grain. Such temperatures are fatal to all stages of the rice weevil (*Calandra oryzae*), and to all stages but the adults of the common granary weevil (*Calandra granaria*), and even these will usually die if exposed for two months or more to temperatures near freezing. Probably larval stages of most insects die if they are exposed to winter temperatures in this country.

If an infestation in its first generation is not completely eliminated by winter temperatures, the sole survivors are likely to be old adults. These, however, will probably be capable of laying eggs, and since these will be laid in early summer, the chance of survival beyond the first generation will be very high. If the infestation is well buried in a large bulk of grain, minimum winter temperatures are unlikely to be reached, both because the grain cannot easily lose its own heat and because the insects themselves are generating heat. If extreme cold is avoided in this way, some larvae or pupae may survive; such survival will of course be aided if there is any artificial heating.

The chief dangers which the weevil population must surmount if it is to establish itself in a bulk of grain are over when most of the first batch of larvae reach their fourth stage. Weevils have four larval stages, and the fourth stage produces considerable amounts of heat. The temperature rise which this heat produces hastens their own development to maturity and accelerates the growth of the younger ones. The amount of temperature rise will be closely related to the density of the population.

As insect development causes a rise in temperature, which increases the rate of insect development, a self-accelerating process is initiated as soon as an insect infestation has established itself in a bulk. Any slight differences in the original density or rate of egg laying, or

in local conditions of humidity or temperature, become enormously exaggerated and the typical patchy development of infestation in " pockets " is produced.

It is probable that much of the patchiness of insect infestation development in bulk grain is due to this cause, but a similar result can also be caused by the mixing of grain of various densities of infestation in the course of ordinary grain handling procedures. It is impossible, at present, to assess the relative importance of these two causes.

Once temperatures above 18-20° C. have been established in this way, deep in a bulk, the infestation can develop in spite of winter temperatures outside. So long as the temperatures are below the optima for development and metabolism, multiplication is most rapid at the thermal centre of a developing infestation. Hence, temperature rise is very rapid at the centre and the optimum is soon passed. Since larvae of grain weevils and of some other grain insects (see Chapter 12) live within the grains, they are unable to leave an unfavourable region ; the temperature therefore continues to rise to levels which are highly unfavourable to the insects and eventually they are killed. This appears also to be true, at least in part, when the infesting insects are free-living and are presumably free to migrate, perhaps because the temperature rise is too rapid for most of the insects to escape.

Although the insects are killed and presumably produce no more heat, the grain does not usually get cooler, since the same process of heat production leading to death of the insects is continuing in an ever-enlarging sphere around the central core, so that there is no cooler grain available to which heat can be lost. Exceptions occur when the hot region is close to the edge of a bulk and the infestation does not progress equally in all dimensions away from the centre.

A developing infestation thus produces highly unfavourable conditions, becoming fatal, at the centre of the infested region. The hot region is surrounded, however, by a falling temperature gradient in which ideal conditions for development are present, not only of temperature but probably also of humidity, since movement of water occurs from the hot centre towards the cooler periphery. In this region of ideal conditions, development is very rapid, so that rapid extension of the infested area is encouraged. This fact, coupled with the tendency for all free-living insects to migrate from excessively hot, dry conditions to cooler and damper regions, is probably a major factor in promoting the spread of infestations once they are well established.

It is thus seen that insects developing in bulk grain progress slowly and precariously at first, but once they are established they spread very rapidly. The grain is heated up by their body heat until a majority are killed, but the remainder survive and are driven to the surfaces of the bulk, where they may appear very suddenly and

unexpectedly. This process is that which the writer has elsewhere called "dry grain heating," and it is characterized by its *maximum* temperature which is always in the region of 38° C. to 42° C. (approximately 100° F. to 107° F.). This temperature cannot be exceeded by insect infestation alone, because it is sufficiently high to kill the insects and thus cut off the source of further heat.

CHAPTER 12

THE MORE IMPORTANT GRAIN INSECTS

It is now appropriate to consider the most important insects which may infest grain in bulk or other storage. There will be no attempt to cover the complete range of possible insects, since the vast majority are so unimportant that they may usually be neglected. It is proposed to refer only to the following insects .—

(1) *Calandra granaria* L ... ... Granary weevil.
(2) *Calandra oryzae* L ... ... Rice weevil.
(3) *Rhizopertha dominica* Fab ... Lesser grain borer.
(4) *Oryzaephilus surinamensis* L ... Saw tooth grain beetle.
(5) *Læmophloeus ferrugineus* L ... Red rust grain beetle and others.
    and other species
(6) *Tribolium* species ... ... Flour beetles.
(7) *Latheticus oryzae* ... Long-headed flour beetle.
(8) *Ephestia elutella* ... ... Cacao moth.
(9) *Tinea granella* ... ... Corn moth.
(10) *Sitotroga cerealella* ... Angoumois grain moth.

It is also considered unnecessary to give detailed descriptions or to provide means for identification of the insects, since this ground is already covered adequately in other works. Of these, the reader will probably find the following the most convenient :—

"Common Insect Pests of Stored Products," by H. E. Hinton and A. Steven Corbet. British Museum (Natural History) Economic Series, No. 15 (1/-).

"Insect Pests in Stored Products," by H. Hayhurst. Chapman and Hall, Ltd., London, 1940 (15/-).

After a brief description of each species, it is proposed to deal with the insects entirely from the point of view of their biology, since it is this which determines the way in which they infest grain and the type of damage which they cause, and also it is the aspect of the insects which is most appropriate to the general title of this book. Furthermore, the biology of the grain insects has received less attention in other works than the importance of the subject deserves.

The Granary Weevil (*Calandra granaria*)

This insect is probably capable of causing more damage to stored grain than any other, although at the present time, owing to rigorous elimination of infested stocks and reduction of infested imports, it is of relatively minor importance in Britain. But, taking the world

as a whole, it is probable that this insect and the closely related Rice weevil, between them, cause more damage to grain stocks than any other grain pest. Changes in the pattern of the grain trade in this country, and changes in our sources of supply might, at any time, bring the granary weevil back to a pre-eminent place among the insect destroyers of grain in Britain, and hence it is most important that the biology of this insect should be thoroughly understood.

DESCRIPTION.

The head is prolonged forward between the eyes into a long snout (this is the distinguishing characteristic of true weevils), at the tip of which is the mouth. The antennae have distinct "elbows" and are "clubbed" at the ends. The insect is $1\frac{1}{2}$ to $3\frac{1}{2}$ millimetres long, and dark brown, or black in colour. The hind part of the body is covered by two hard wing cases (characteristic of all beetles), but there are no true flying wings.

LIFE HISTORY.

The adult female bores a small round hole in a wheat grain by means of the mouth parts on the tip of her snout. In this, she lays a single egg and immediately plugs the hole with a mucilaginous material. It is not easy to see the plugged hole, particularly if it is among the hairs of the "beard," so that it is not practicable to tell by examination the number of grains which have had eggs laid in them. It is possible to stain the gummy material of the plug, and thus make it easier to recognize a grain in which an egg hole has been made, but as the females have a habit of making and plugging some holes in which they do not lay eggs, this method is not very useful.

The egg hatches to produce a small larva which lives in the endosperm of the grain. The larva moults three times, so that there are four larval stages of which the fourth is much the largest and most active. The differences in size and activity are shown by the carbon dioxide output of each stage which is quoted below from Howe and Oxley (1944) in terms of the number of individuals required in a pound of grain to produce a one per cent. carbon dioxide concentration:

1st stage larvae	...	160 individuals per pound
2nd stage larvae	...	80 individuals per pound
3rd stage larvae	...	35 individuals per pound
4th stage larvae	...	6-10 individuals per pound

The larva lives throughout its life within the grain and normally makes no hole in the bran, so that it is impossible to detect an infested grain by inspection. The fourth stage larva, however, has a remarkable habit of boring a hole in the bran and ejecting frass (i.e. excreta) from the grain if the carbon dioxide concentration exceeds a certain level. This is described by Richards and Oxley (1943), who found that fourth stage larvae were most sensitive in the middle of the duration of the stage. They also found that the most effective concentration of carbon dioxide lies between five and ten

per cent., but it is common for the larvae to eject frass under lower concentrations than these.

This habit may be used to detect the presence of fourth stage larvae of granary weevils thus: (1) Place a small amount of suspected grain in a dish not more than half an inch deep, allowing the grain to be in a layer only one grain deep on the bottom. (2) Seal the dish by covering it with a sheet of glass and making a truly airtight joint with the dish by means of vaseline, plasticine or wax. (3) Examine the grain at intervals up to two or three days. If the amount of air sealed up with the grain is small and there are weevil larvae present, a carbon dioxide concentration high enough to cause ejection of frass will soon be built up and little white piles of dusty frass will appear beside the grains which contain fourth stage larvae.

This method of detecting fourth stage larvae is interesting and instructive, but is not very useful in practice, because there will usually be relatively few weevils in this particular stage of their life history at any one time. It may be used by students, however, to find which particular grains contain fully grown larvae if it is desired to see them by dissection of the grains.

It is noticeable that a weevil larva will eat out nearly the whole of the endosperm of a wheat grain but will not usually enter the germ which appears to be distasteful to them; in the case of maize, it appears that the germ is actually toxic to the larvae. It is possible for two larvae (and rarely a third) to complete their life history within a single wheat grain if it is sufficiently large, but such larvae do not grow to their full size and they give rise to small adult weevils. Two or more larvae will not usually develop simultaneously in the grain, as one will often eat the other, but it is possible for them to develop consecutively, i.e. for an egg laid in a grain which has already been the home of one larva to develop to a small but healthy adult weevil. Maize grains can support the growth of a number of larvae to full size.

The fourth stage larva eventually produces a thin-skinned and fairly active pupa whose carbon dioxide production is about the same as that of a third stage larva. The pupa, of course, does not eat.

The pupa gives rise to an adult weevil which escapes from the pupal skin and usually remains within the grain for a day or two. This newly-formed adult is full size (since adult insects do not grow), but its skin is thin and brown and does not become black for several days. The adult bores a hole in the wall of the hollow grain large enough for it to escape, and this is the hole which is commonly observed in weevilled grain. Thus, a grain which has a hole is one which has already produced a weevil and probably no longer contains an egg or larva. The young adult is not sexually mature at first, though if it remains for several days in the grain it may be mature by the time it emerges. Mature males and females wander freely between the grains and mate as soon as possible; thereafter, the female can lay a succession of fertile eggs for a long time.

The exact duration of the life history of weevils, and of the various

parts of it, are not precisely known, but approximate figures can be given as below. In reading these, it is important to keep in mind that, under any particular physical conditions, there is a very wide spread in the length of life history, so that any figure given must be an average only. In general, rate of development increases with increasing temperature up to about 28° C. (82·4° F.) and with increasing humidity up to the highest levels. The only limit to the advantageous effect of high humidity is set by the development of moulds and bacteria which occurs rapidly when the water content of grain exceeds about 20 per cent. or the relative humidity 90 per cent.

At 21° C. (69·8° F.) and 70 per cent. relative humidity, the following mean periods apply to the granary weevil:

Egg	5 days
1st larval stage	6 days
2nd larval stage...	7 days
3rd larval stage	12 days
4th larval stage	14 days
Pupal stage	7 days
Adult remains in grain ...	4 days
Total, egg to free-living adult	55 days

As an illustration of the "spread" in life history, it may be mentioned that, under these conditions of temperature and humidity, the first adults might be expected to emerge from the grain within forty days from the date when the eggs were laid, while the last might not appear until seventy to eighty days had elapsed. While the majority would appear within a few days on either side of the fifty-five days mean period suggested above, it is clear that odd individuals, sufficient in some circumstances to upset a system of hygienic management of grain stocks, will behave very differently from the majority.

Study of the published literature on the subject shows that there has not been adequate work on the life history of the grain weevils, but from experience, the following mean periods for the total life history at 70 per cent. relative humidity may be suggested:

17° C. (62·6° F.)... ...	120-150 days
25° C. (77·0° F.)... ...	35 days
28° C. (82·4° F.)... ...	30 days

HABITS OF ADULT WEEVILS.

The adult weevil eats a small amount of grain, making shallow holes with ragged edges, but the amount of damage which they do in this way is negligible by comparison with the complete hollowing out of grains which the larvae accomplish. The movements of the adults are of some importance, since they determine the direction of spread of the infestation. As explained in Chapter 11, once a heavy infestation producing heat is established in a bulk of grain, the advancing

heat forces the movements of free-living insects irrespective of their normal habits. But the movements of adults before the infestation is dense must determine to a considerable extent the likelihood that infestations will develop deep in the grain or by the walls, floors, or upper surface.

Unfortunately, not much is known about the movements of adult weevils in grain, but the following generalizations are of some help in forecasting the early form of development of weevil infestations.

1. Weevils often show no propensity to wander at all, and if conditions are favourable, they may remain in one region for long periods.
2. When weevils wander, they appear to do so at random in all directions with a general preference for downward movement. When they reach surfaces (upper surface, or walls, or floors), they often stop wandering and in this way they tend to accumulate at the limits of a bulk.
3. When grain containing weevils is disturbed, they move quickly upwards and accumulate on the surface. Sometimes the population of adult weevils becomes great enough for them to disturb each other so that a proportion of them is continually stimulated to move upwards to the surface and the zone of high infestation is marked by a " pullulation " of weevils wandering on the surface.
4. Other things being equal, adult weevils tend to move towards grain which is pleasantly warm (in the neighbourhood of 80° F.) or damp.

There is some evidence that weevils are unable to move freely between the grains of wheat in a bulk when the wheat is small grained and tightly packed, but the restriction probably affects only the largest adult weevils and it is clear that weevil infestations are able to spread even at great depths where the pressure on the grains is very high. There is, of course, ample space for movement in maize and among the grains of large grained wheats, however great the depths and pressures. It seems improbable that the pressure exerted by great depths of grain has any great restrictive effect on the development or movement of weevil infestations.

The Rice Weevil (*Calandra oryzae*)

This insect is very similar in its biology to the granary weevil, and most of the description and biological data given for that insect may also be applied to the rice weevil.

DESCRIPTION.

The size and appearance are very similar to the granary weevil, but the rice weevil may always be distinguished by the following two characters :

1. The prothorax (the portion of the body visible in front of the wings and behind the head) is covered with very fine indentations like the surface of a thimble. In the granary weevil, the prothorax has fewer, oblong, indentations with smooth flat areas between them.
2. The hard fore wings, which cover the whole hind part of the body, have four indistinct reddish brown patches on them.

Two other characteristics which may help to distinguish the rice weevil are its ability to fly (but it will not do this in Britain, except in hot weather) and its ability to climb up clean glass. The granary weevil cannot fly and usually cannot climb really clean glass.

There are two varieties of rice weevil, one of about the same size as the granary weevil and the other considerably smaller. The latter occurs most commonly in grain from South America, but it is also found in Australia and probably in other parts of the world. Richards (1944) and Birch (1944), have both shown that there are big differences in size of weevils according to whether their larvae develop in large or small grained wheats or in maize; the latter produces particularly large specimens. The size differences due to food are as great as the differences between the strains, but the strains remain distinct, for on any particular food the large strain is always larger than the small strain. Some books refer to a "maize weevil" to which the latin name *Calandra zea mais* has been given, but it is very unlikely that this is a distinct species; the differences between it and other weevils are almost certainly due to the fact that the large grains of maize enable the weevils to grow very big. The small strain of the rice weevil is much less prone to eject frass from the grains under the influence of high carbon dioxide concentrations than either the granary weevil or the large strain of rice weevil. Since the small strain is usually predominant in Plate wheat, students who attempt the demonstration of frass ejection described above may be disappointed if they use weevils from this source.

LIFE HISTORY.

In general, the life history of the rice weevil is very similar to that of the granary weevil, but its development is slightly more rapid. In particular, the small strain breeds rather more rapidly than other weevils because the adults become sexually mature sooner.

BIOLOGY.

So far as is known, there are no important differences between the granary weevil and the rice weevil, other than those which arise from the ability of the latter to fly and to withstand rather higher temperatures than the former. The rice weevil is an insect of hotter climates, and at the temperatures common in sub-tropical and hot temperate countries, it habitually flies into the field and lays its eggs in the grain as it ripens on the stalk. This form of infestation, in which the same insect is common both in the field and in the warehouse, is fortunately unknown in Britain and other temperate or cold

temperate climates. Where it occurs, the farmer is faced with the problem of dealing with grain which is infested at the time of harvest, and it is not surprising that grain imported from such countries is so frequently heavily infested with weevils and that these are usually rice weevils.

The higher temperature tolerance of rice weevils is quite small, but it results in their extending further into tropical climates than the granary weevil, which cannot breed at temperatures consistently higher than 30-32° C. (86-89·6° F.). Probably, the rice weevil is responsible for more damage to grain in the world than the granary weevil, although in Britain it cannot build up a permanent infestation except in warmed premises, or in bulks of grain which it is causing to heat.

The Lesser Grain Borer

(*Rhizopertha dominica*)

This animal is of cosmopolitan distribution, principally in warmer climates; in Great Britain it is chiefly found in wheat imported from South America, Australia, and India. In the U.S.A. where it also occurs it is known as the "Australian Wheat Weevil," though, of course, it is not a true weevil.

It is seldom found forming "pure" infestations (i.e., infestations in which it is the only, or almost the only, species present); it is usually found associated with such other common pests as the Rice Weevil, Red Rust Grain Beetle, Flour Beetle, Long-headed Flour Beetle, etc., but it is quite frequently the major constituent of such mixed infestations.

Description.

A somewhat cylindrical, dark brown, beetle, about 2½ to 3 millimetres long, rather slow moving. The head is fixed just below the front end of the thorax and turned somewhat downwards so that it is scarcely visible from above. This gives the insect a headless appearance and it appears to consist merely of two parts joined by a waist. The antennae are easily visible, however; they are distinctly "clubbed" and each "club" consists of three very obvious segments.

Biology.

The lesser grain borer is biologically similar to the grain weevils in that the larva lives within the grain where it develops, pupates, and finally emerges as an adult. It differs from the weevils, however, in that the egg is laid externally to the grains where it hatches and produces a first stage larva. This larva usually wanders a short distance from where it was hatched and then bores its way into a grain. It prefers a crack for this purpose but will enter undamaged wheat grains, through the embryo if possible, though it is able to bore

through the bran. The larva can even enter a maize grain through the thick, hard skin if there is no alternative, but this requires a day or two. Once a larva has entered a grain, it usually remains there for the remainder of its life.

The duration of the life history is probably about 10 to 20 per cent. longer than that of the granary weevil at the same temperature and relative humidity. Few exact data obtained at controlled temperatures and humidities exist, but according to Crombie (1941), the total life history is completed in about 35 to 40 days at 30° C. and 70 per cent. relative humidity.

The lesser grain borer has a somewhat higher temperature range than the granary weevil, being less tolerant of low temperatures and more tolerant of high temperatures. Probably, its upper limits are somewhat higher than even those of the rice weevil. For this reason, it does not establish endemic infestations in British warehouses, though it is, of course, possible for it to survive throughout the summer and it may thus infest clean grain placed in a warehouse before autumn even if the infested grain which was the source of the insect was removed in spring several months before.

As a causative agent for heating in grain, the lesser grain borer is somewhat less effective than either of the weevils ; this is conveniently measured by the carbon dioxide production of the insects. That of the adults is compared in the table of Howe and Oxley (1944) where it is seen that thirty adults of granary weevil are equivalent in carbon dioxide production to sixty adults of the lesser grain borer.

In a mixed larval infestation, each lesser grain borer individual is considered to be equivalent to one quarter of a weevil. Probably this is an underestimate, but certainly the two insects are considerably different in this respect. A dense infestation of lesser grain borers, however, can, and occasionally does, cause serious heating.

The damage caused by the lesser grain borer is easily distinguished from that caused by weevils. This is largely because the adult beetle is a voracious feeder as well as the larva and in its feeding it makes large irregular holes which eventually break up the grains altogether. This insect is a member of a family of wood borers and it is perhaps for this reason that the adult appears to chew up a great deal more grain than it needs for its food.

One or two other points of interest concerning this insect are worth mentioning. Firstly, this insect has in some investigations been found to be more common than other insects at or near the bottom of bulks or bins ; it may be that it is specially well adapted to this situation. Secondly, the adults appear to be particularly fragile, a considerable proportion being broken by mechanical action when grain bulks in which they are living are severely disturbed. It is possible that this insect could be more effectively controlled than most by turning grain repeatedly. Thirdly, the wood boring habit of this insect sometimes leads it to penetrate slightly into the walls of wooden bins in which grain heavily infested by it is stored.

The Saw Toothed Grain Beetle

(*Oryzaephilus surinamensis*)

This insect is also quite frequently known by the name *Silvanus surinamensis*, but the above name though more difficult to pronounce, is more correct and, being now widely accepted, should always be used.

DESCRIPTION.

The common name is rather misleading; it does not refer to the jaws or mouth parts but to the toothed edges of the prothorax (i.e., the middle section of the body) by which it can be recognized easily. It is small, narrow, flat, and brown, about 2½ to 3 millimetres long. Although it is about as long as a lesser grain borer or a rice weevil, it is very much smaller, flatter, and narrower than either of these.

BIOLOGY.

The insect is a fairly common pest of a wide range of stored products, including grain, but it seldom appears as the major constituent of a serious infestation. Nevertheless, occasionally, under suitable conditions, it may breed up to very large numbers in grain and cause heating. It is thought that it can never be a primary pest of grain because it appears to live only in the dust and small fragments produced by the attack of other insects. In hot climates, it flies regularly and spreads in this way; in Britain, flight is uncommon. The larvae are always free-living among the grains which they do not enter unless they are already holed by other insects.

The Red Rust Grain Beetle and related Species

(*Laemophloeus ferrugineus* and other species)

There are several species of this insect which infest grain, and "common" names have been invented for two or three of them, but there is at least one species known to cause serious infestations and heating in grain which has not yet been identified and has no English name. Hence it will be more convenient to refer to all the grain-infesting species under the generic Latin name *Laemophloeus* and avoid specific distinctions and common names altogether.

In many respects these various species are sufficiently similar for their biology to be covered by a single account and certainly no warehouse-keeper need bother to distinguish them.

DESCRIPTION.

Very small and flat (distinctly smaller than *Oryzaephilus*) with long conspicuous antennae about three-quarters the length of the body. Body length is about 1½ to 2 millimetres.

BIOLOGY.

Laemophloeus is very widely distributed wherever grain is stored and also in flour and provender mills. Generally, it has been known

as an unimportant insect which, though frequently present, is not responsible for any measurable amount of damage. This view, however, has had to be modified in recent years in connection with grain storage, particularly in Canada and Great Britain. In the great stocks which were built up in Canada during the war, serious infestations by *Laemophloeus*, causing heat and damage, occurred several times and similar outbreaks occurred in this country. Such an infestation was studied by Lucas and Oxley (1946), whose findings form the basis of the following account.

Laemophloeus lays its eggs externally to the grain and, until recently, it was thought that the larvae remained free-living throughout their lives. The implication of this belief is that the density of infestation could always be assessed by examination of a sample since all stages would be visible. Also, if the larvae were always external to the grain, it would appear that they could live only on dust and debris and would be incapable of acting as primary pests of grain. Investigation showed, however, that under normal conditions of active infestation in wheat, the larvae are able to enter undamaged grains and spend all, or nearly all, their life within them. The larvae enter the germs of the wheat grains and spend their lives in this situation without invading the endosperm, which is in contrast with the behaviour of weevil larvae.

The larvae are not obliged to remain within the grains, however, and a small proportion usually escape and live freely for a part of their lives. This may depend simply on the size of the entry hole or the extent to which the larva is disturbed by other larvae or adults. The proportion of the total population of larvae which is found wandering freely among the grains of a sample at any one time is very variable indeed and is therefore not a useful measure of the total population.

Laemophloeus lives more successfully on flour than on whole grain, which suggests that it is by nature a dust feeder, and probably no infestation of whole wheat would be possible (unless other insects had first broken the grains) if the insect was not able to enter the grains. In earlier laboratory investigations *Laemophloeus* appeared to be unable to enter undamaged wheat grains, but recent experience of infestations show that this is certainly not true in some circumstances, and if the serious depradations which this insect has caused in recent years are to be avoided in future, it is most desirable that the conditions which enable it to enter the grains should be discovered. It is possible that a localized high humidity is essential for the first entry and that subsequent spread is facilitated by the extending circle of dampness which surrounds a heating patch. Alternatively, it may be possible that a high temperature is itself sufficient to enable the larvae to enter the grain even without any extra dampness.

The temperature range of *Laemophloeus* appears to be somewhat higher than that of the grain weevil and possibly higher than that of the rice weevil. Its life history length is not precisely known for any particular combination of temperature and humidity, but complete " breeding out " appeared to have been achieved by Lucas

and Oxley after six weeks at 28° C. (82·4° F.) and 70 per cent. relative humidity. The mean life cycle is presumably somewhat shorter than this under these conditions.

The Flour Beetles (*Tribolium species*)

There are three species of the genus *Tribolium* which occur very widely in most parts of the world, chiefly in flour and other crushed cereal products. They are not primary pests of grain since they cannot breed in unbroken grain, but they occur quite frequently in association with such primary pests as weevils and the lesser grain borer. They are a characteristic member of the typical insect fauna of " Plate " grain imported into this country. The life history lasts about five to seven weeks at 25° C. (77° F.) if the humidity is not too low.

DESCRIPTION.

Smooth, reddish-brown beetles, 3-5 millimetres long, i.e., slightly longer than granary weevils but probably no larger than these in body bulk. Antennae relatively short and somewhat clubbed at their ends.

The Long-headed Flour Beetle (*Latheticus oryzae*)

This insect is, biologically, very similar to the *Tribolium* flour beetles in that it lives for preference in flour or grain debris and occurs fairly frequently as a secondary pest of stored grain which has already been broken into by primary pests. It is also similar to *Tribolium* in appearance but is rather narrower and longer in the abdomen and wing cases. The length of the head, which is referred to in the common name, is not a very conspicuous feature and is not very helpful to the layman for identification. The antennae are noticeably shorter and thicker than those of *Tribolium*.

The long-headed flour beetle appears to be particularly well adapted to life in grain which has been caused to heat by the activities of other insects. It is unusually tolerant of high temperatures and high carbon dioxide concentrations, so that it is able to maintain heat production in conditions which might be fatal to most of the primary grain pests. It has been noticed that the numbers of this insect often increase relatively to those of the primary pests in the later stages of grain heating, and this is probably due to its greater tolerance of the adverse conditions.

The Grain Moths

There are two moths of considerable economic importance in grain storage and quite a number of others which frequently live on grain but usually cause very little damage. Of the latter, it is proposed to mention only one, the Corn Moth, because it is probably the most important of the minor moth pests of grain in Britain. The three which are dealt with are :—

1. The Angoumois Grain Moth (*Sitotroga cerealella*).
2. The Corn Moth (*Tinea granella*).
3. The Cacao Moth (*Ephestia elutella*).

From the point of view of grain storage in Great Britain, these are in ascending order of importance, but from the world point of view, it is probable that the order should be reversed.

Millers may wonder at the exclusion from this list of the Mediterranean Flour Moth which is one of their worst pests. The reason is that this moth is primarily a pest of flour in warmed places. It is able to infest grain, but only if it is stored in heated premises, and in fact it is only a very minor pest indeed of grain in normal storage.

The Angoumois Grain Moth (*Sitotroga cerealella*)

This moth, whose common name comes from the district in France where it was first found to be infesting grain, is widely distributed in warm temperate parts of the world but, so far as the writer knows, has never established itself in Britain. The limiting factor is probably the cool summer of Britain, not the cold winter, for the larvae are able to survive the winter in grain in the northern states of the U.S.A. with much lower temperatures. Our summer is probably unsuitable for the normal completion of the life history described below, but it seems possible that a serious infestation by this pest might be established after an unusually warm summer, and it is for this reason that the writer considers it worth while to give more detailed attention to this insect than has been given to others which are at present of negligible importance in Britain.

DESCRIPTION.

A small yellow or brownish yellow moth with rather narrow wings whose spread is about 10 to 14 millimetres.

BIOLOGY.

The life history is of the same kind as that of the Lesser Grain Borer (*Rhizopertha dominica*) in that the eggs are laid externally to the grain, and the young larva enters the grain and lives its life within it. The eggs are laid either singly or in little clusters, and the site in which they are laid depends very much on the circumstances of the infestation. If the moth is flying in a closed warehouse over an exposed grain surface, it will willingly lay eggs directly on the grain, but if it is flying in fields (as usually happens in the warm climates where the moth is a major pest), it will lay on young or old ears of growing wheat or maize, or on the leaves, straw or ears, of stooked grain.

The young larva is said to find some difficulty in entering a dry undamaged grain and will often spin a little silk cocoon against the bran in order to help it to exert sufficient pressure to effect entry.

It may be that no serious infestation could establish itself in dry undamaged grain because of the difficulties involved whereas, if the larva has access to soft unripe grain in the field, entry would be easy and an infestation could be established. Perhaps failure of the insect in this country depends on the lack of suitably favourable weather for the flight of the moths in large numbers into the field at the right time.

The larva develops within the endosperm of the grain, leaving the germ untouched, and passes through four larval stages before pupating. When it is ready to pupate, the larva prepares an exit hole to the exterior and closes it with a flap of bran and some silk; in this process, other grains may become stuck to the infested grain. Then, remaining within the grain, the larva pupates. When the adult moth emerges from the pupal skin it escapes easily through the prepared hole.

The moth does not eat any grain and it lives for only a few days; in both respects it differs from the Lesser Grain Borer and the Rice Weevil to which it is otherwise similar biologically in so many respects. The shortness of the adult life is important, because it means that unless conditions are suitable for egg laying during the period when the moths are emerging, there will be no survivors to carry on the infestation.

Grain, both maize and wheat, containing larvae and pupae of the Angoumois Grain Moth is quite frequently imported into this country and the insect may perhaps, in some cases, have been responsible for some heat in the bulks. It is rather unlikely, however, that these larvae could have been actually generating heat in this country because the life history would in most cases have been largely completed on the ship during transit, and the opportunities for egg laying by any adults which emerged in the grain while it was in bulk would have been very slender. Probably, adults which emerge from grains deep in a bulk would be unable to escape to the air, and hence infestations by this moth may be considerably restricted after passing a single generation if the grain is gathered into large bulks.

With this insect, as with the rice weevil, the farmer in warm climates is confronted with the problem of dealing with grain which is infested at the time of harvest. This is perhaps the greatest advantage that the insect has as a grain pest, but it is largely offset by the fact that infestation in the field is the only way in which it is likely to be able to reach really large numbers in grain bulks.

The length of the life history has not been thoroughly investigated at a range of controlled temperatures and humidities, but Crombie (1943) has reported a study made at 30° C. (86° F.) and 70 per cent. relative humidity. These data are reproduced below as they are probably the best at present available, although the moths were reared on flour, which is not their normal food, and mortality was high:

Life history stage	Mean period	Range
Egg	3 days	2 to 7 days
1st stage larva	6 days	4 to 10 days
2nd stage larva... ...	6 days	4 to 10 days
3rd stage larva ...	5 days	2 to 9 days
4th stage larva... ...	7 days	6 to 12 days
Pupa	5 days	4 to 7 days
Total period	32 days	30 to 40 days

These figures agree with the common statement that the life history under favourable conditions occupies about five weeks.

The Corn Moth (*Tinea granella*)

The Corn Moth is known in America as the "European Grain Moth" and frequently the alternative Latin name *Nemapogon granella* is used in that country.

DESCRIPTION.

A small moth, scarcely larger than the Angoumois Grain Moth, with creamy white body and wings, the fore wings being heavily mottled with brown. The mottling on the fore wings forms irregular bands which run backwards and outwards from the front edge of the wing.

BIOLOGY.

The details of the biology of this moth are not well known. So far as is known, the eggs are laid among the grains in store and the larvae live freely without entering the grains. They probably eat both germ and endosperm and they appear to develop more rapidly when the grain is somewhat broken than when it is whole.

In the course of their feeding, the larvae spin a certain amount of webbing which binds the surface grains loosely together to give a "crumby" effect. In this they are similar to many other moths which can live on grain, but a distinctive difference from these is the habit which the Corn Moth has of pupating "on its head," i.e., the pupa sticks out at right angles from the surface of the grain or bags. a heavy infestation produces quite a forest of pupae which is particularly noticeable on bags.

The Cacao Moth (*Ephestia elutella*)

The Cacao Moth has an interesting history of infestation. As its name implies, it is well known as a pest of cacao, but it is also common on stored tobacco and has been recorded as an occasional pest from a very large number of other products.

In the period before the 1914-18 war it was never regarded as a grain pest, although it was known to include grain among the wide variety of products on which it was able to live. During that war,

however, the phenomenon of "webbing" of grain was first noticed and shown by Dendy and Elkington (1919) to be due to infestation by *Ephestia elutella*. Webbing was apparently not very common at that time, and in the period between the wars it was not reported at all. In the second war, however, the phenomenon assumed more serious dimensions in Britain and, in fact, *Ephestia elutella* became one of the most serious pests of grain in the country.

Thus an insect which at other times was of negligible importance was able to become a very important major pest during each of the two world wars. It is clear from a study of the biology of the insect and of the circumstances in which the infestation arose, that the feature of war-time conditions which so completely changed the status of this insect was the prolonged storage of parcels of grain and repeated use of the same stowages for grain.

DESCRIPTION.

A greyish brown moth, about 14 to 22 millimetres long. Somewhat variable in depth of colour, varying from pale grey in a few specimens to some which are almost entirely brown. Two faint pale lines, dark on their outer edges, cross the fore wings, one rather obliquely, the other transversely.

BIOLOGY.

The biology of this insect is different from that of any of the others dealt with in the present series of articles and was until recently very inadequately known, but the publications of Richards and Waloff (1946) have now elucidated all the essential features.

The eggs are laid on the surface of the grain, each female laying between 50 and 200 eggs, the average number being in the region of 100. This occurs during early and mid-summer. The eggs hatch, and each minute first stage larva attacks the germ of a grain which it hollows out and enters. The first two larval stages are spent inside the hollowed-out germ of the grain which was first entered, but after the second moult, the larva is too big to remain in this situation and thereafter it progresses from grain to grain eating out the embryos (germs).

In the course of its life, each larva eats the germs out of about 48 grains, producing a characteristically neat, clean, hollow with no ragged edges of bran. In hard wheats, the larvae attack only the germs, but in soft English wheats, some endosperm is eaten. In the course of their feeding progress, most larvae do not wander more than a foot or two, and since the eggs are laid on the surface of the grain, this results in damage being greatest in the top twelve inches. A number of larvae, however, wander deeply down into the grain and some penetrate to a depth of six feet or more. Although the proportion of grains damaged at depths greater than one foot is small, the total number of damaged grains at such depths is quite a large proportion of the total damage.

There are five or six larval stages. When these have been completed

and the larvae are ready to pupate, their habit of random wandering from grain to grain in search of food changes suddenly and they develop a very powerful urge to move upwards. Thus it happens that in late summer, usually in September or late August, the surface of the grain which has previously appeared uninfested, suddenly becomes a crawling mass of mature larvae. Each larva is searching for a route to climb upwards and although a few reach the walls or various pillars and so gain the ceiling immediately, the majority wander on the surface of the grain for a long time before finding a route to the ceiling. They concentrate chiefly on the highest points of the grain surface, i.e., the tops of heaps. Each wandering larva spins a continuous silken thread wherever it goes so that the surface of the grain, and later the walls and ceilings, become covered by a thick continuous mat of webbing.

In a bad infestation, many thousands of larvae die on the surface of the grain, chiefly from an infectious disease called " wilt." The dead bodies impart a particularly disgusting and penetrating smell to the bulk and the combination of this with the continuous webbing sheet, the dead and dying larvae, and their excrement, on the grain, give the impression of a disastrous event which has overtaken the grain. This impression is the stronger because it occurs without warning during the course of a week or two.

In fact, the amount of damage caused is less than appears at first sight, but there is a serious loss of germ material, labour is needed to remove the webbing sheet with which some grain is inevitably removed also, and the webbing which cannot be removed tends to clog elevators and spouts. The accumulation of webbing and larvae in the fabric of the warehouse is also an inconvenience, especially if it is repeated for a number of years.

Most larvae which do not die of wilt eventually gain the ceiling or other high spot where they seek cracks and crevices of a suitable size for pupation. Most eventually find such cracks, and those which do not, remain on an exposed surface. The larvae do not pupate immediately ; each spins for itself a silken cocoon and therein it passes into a state of coma called " diapause." The larvae remain in this state throughout the winter and do not pupate until spring in the following year. The pupal period lasts for three to four weeks and then the adult moths appear. They pair very soon and egg laying begins immediately and continues throughout the life of the female moths which averages about twelve to fourteen days.

The moths are not very conspicuous, particularly as they fly chiefly at dawn and dusk, and many warehouse-keepers pay little attention even to considerable numbers of them in the vicinity of bulk grain in early summer. But, owing to their high multiplication rate, even a relatively small flight of moths gives rise to a tremendous larval population in September.

The life cycle described above should be borne in mind when control measures are to be applied or when it is desired to move or

mill grain to the best advantage from the point of view of control of the pest.

It will be noted that about mid-summer, before wandering larvae appear, the whole population is in the grain and can be got rid of by putting the grain into consumption at this time. A few months later, however, in late autumn, the entire population has left the grain and is in the fabric of the warehouse. Moving the grain at this stage has no effect whatever and it is safe to leave it until the first moths appear in late spring.

CHAPTER 13

MITES AS PESTS OF STORED GRAIN

Most men who are responsible for grain storage have heard of mites and many have suffered from their depredations, though in some cases the damage may have been very slight and in others may not have been recognized as damage at all. Mites are exceedingly small and inconspicuous, however, and some who recognize the typical taint and damage may never have seen the animals themselves.

The importance of mite infestation in grain is a subject on which there has been some dispute, though in the worst cases the grain reaches a condition which no one could fail to recognize as deteriorated. The very frequent mite infestations which do not reach an extreme stage, however, are less obviously deleterious and it will be as well to summarize the evidence that the presence of mites is, or may be, undesirable before discussing the nature of the infestations (see also the review of information on mites by Solomon, 1943).

(1) The characteristic smell of grain or other products which contain *Tyroglyphus farinae* (the commonest and most important mite on grain) is well known. It is repugnant to most people and very penetrating, though it disappears quite quickly from most products after death of the mites.

(2) Mites consume the germs of wheat, and if the infestation is severe, the entire germs may be removed from many or all of the grains with a consequent loss of much of the fat and vitamin content.

(3) In common with all other organisms living in grain, mites produce an amount of heat which frequently cannot escape without appreciable warming of the grain. The writer has not, however, observed very high temperatures being produced in bulk grain by mites. There are three reasons for this. Firstly, mites tend to be distributed superficially in the bulk and do not penetrate to depths sufficient to cause serious heating. Secondly, the maximum temperatures which mites are able to withstand are lower than those of most insects. Thirdly, since mites live only on the germs of grain (which are only about 2½ per cent. of the whole grain in wheat), really heavy infestations such as are necessary to cause heating, often exhaust the available food supply at any point before they have had time to produce high temperatures.

(4) Materials which are, or have been, infested by mites have frequently been reported to cause " scouring " in animals and similar intestinal disorders in man. Contact of the skin with mites is in some cases responsible for dermatitis. Many allegations of intestinal troubles due to mites are difficult to prove or disprove, but the sum of evidence certainly suggests that the presence of mites in any food

material is most undesirable. For this reason, mites are obviously more important in flour or other cereal products than in the grain itself, but since it is highly probable that mites are sometimes able to pass through the milling process and develop in the flour made from mitey wheat, their presence in grain must also be regarded as medically undesirable.

(5) If mites are allowed to develop unchecked in grain, there will be a serious danger of transfer of the pest to other goods in which their presence is more directly injurious.

(6) The removal of the germ from wheat obviously kills the grain and thus ruins it for seed purposes. Also, dead grain must be regarded as suspect for milling purposes.

Recognition of Mites

Mites are not insects, but are closely related to spiders. The reasons for this distinction are unimportant for the present purpose, but the layman will appreciate the evident distinction that, whereas mites and spiders have eight legs and no wings, all insects have six legs and most have wings. It must also be noted that mites are very small indeed, many being scarcely visible to the naked eye, though most can easily be seen with a hand lens. Fully grown mites of the species important in grain are about ½ to 1 millimetre long.

There is some tendency in the grain trade to confuse mites with Psocids (book lice) which are quite common, and apparently largely harmless, in bulk grain. The latter are true insects considerably larger and generally much more active than mites.

In top view, the bodies of mites are rounded or egg shaped with the head continuous with the body (i.e. no distinct neck) and somewhat flattened in side view. They are more or less transparent and very thin skinned. Usually, they are provided with a number of hairs or bristles which in some cases may be almost as long as the body.

Although there are many families and species of mites which may occasionally be found in grain, only a few of these are of any importance in causing deterioration. It is proposed to mention the following mites which are the ones most commonly found :—

1. *Tyroglyphus farinae.*
2. *Glycyphagus destructor.*
3. *Cheyletus eruditus.*
4. Gamasid mites.

Tyroglyphus farinae

This mite is most easily recognized by the following characters:

(1) Size. Slightly smaller than any of the other three. About 0·4 to 0·5 millimetres long excluding the hairs.

(2) Brown legs. Varying between light and dark brown, but always much darker than the rest of the body. In the male, a further

noticeable feature is the fact that the front legs are considerably swollen.

(3) Slowness of movement.

(4) Shortness of the hairs. The hairs are short by comparison with many mites, but as most are considerably hairy, a layman who had seen no other mites would certainly describe *Tyroglyphus* as "long haired."

(5) Distinctive smell. This character is very easily recognized and is unique among the mites found on grain. The smell is due to an oily secretion which the mites produce, possibly from a pair of glands which can be seen on their backs. The smell is most easily detected if infested grain is rolled or squeezed in the hands so as to crush the bodies of a number of the mites. All who have charge of grain stocks should make a point of learning to recognize this smell (which is sometimes known as "mintiness" or "mint") particularly if storage conditions are somewhat damp. The smell disappears fairly quickly from most products after removal or death of the mites.

Glycyphagus destructor

This mite may be distinguished from the others by the following characters:

(1) Size. The body is generally slightly larger than that of *Tyroglyphus*, but smaller than that of either of the other two mentioned here.

(2) Long Hairs. This is a very hairy mite and is easily distinguished from the others on this ground alone. Owing to the hairiness, it appears at first glance to be much larger than *Tyroglyphus*, although the body size difference is slight.

(3) Rapid Movements. *Glycyphagus* moves about rapidly with short, apparently aimless, jigging movements. Because of the irregular direction of its movements, the distance covered in any one direction is probably usually no greater than that of the slow moving *Tyroglyphus*.

Cheyletus eruditus

This mite may be distinguished from the others mentioned by the following characters:

(1) Size. It is larger than either of the preceding mites, being often as much as one millimetre in length when fully grown. Also, the legs are longer in proportion to body size than those of the others.

(2) Movements are often rapid, but much less erratic than those of *Glycyphagus*.

(3) There is a pair of claws, one on each side of the head, which approach the legs in size. These are held up from the ground but might otherwise be mistaken for an extra pair of legs. The mite is

predatory (i.e., it lives on other mites), and it may often be recognized by the fact that it is found holding the remains of its prey in its front claws.

Gamasid mites

This is a group of mites various species of which commonly occur in grain. For the present purpose, it is unnecessary to distinguish the species ; it will be sufficient in any particular case to recognize that Gamasid mites are, or are not, present. Mites of this group may be distinguished from the others mentioned by the following characters :

(1) Size and General Appearance. Gamasid mites are considerably larger than the other three species mentioned, and in general appearance they much more closely resemble spiders.

(2) Short hairs cover most parts of the body as is the case with spiders.

(3) Colour. Both body and legs are brown.

(4) Rapid running like a spider.

Life History and Biology of Mites

There are several distinctive features of the life history and biology of mites which are common to all those found infesting grain, but before considering these, it will be useful to note the special biological characteristics of the four mites which have been mentioned.

Tyroglyphus farinae is essentially a grain and flour eater, although it is often found on other materials. It attacks the germs of wheat grains and hollows them out, but it does not remove the overlying bran completely, so that a ragged edge remains over the hollow. This distinguishes damage by mites from that caused by many moth larvae which usually remove the bran quite cleanly over the germ. *Tyroglyphus* usually infests all kinds of grain when conditions are suitable and is also common on flour.

Glycyphagus destructor does not attack whole grains. It is believed to live almost entirely on dust derived from the grains or on flour. Owing to its long hairs, however, this mite is unable to penetrate into stored flour and is, therefore, not a serious pest of this commodity.

Both the above mites are known to live on fungi (mould) when these are available and this may be the major food of *Glycyphagus* in some cases. The presence of either or both of these mites may, in some cases, explain the apparent lack of mould development on grain which is very damp and would normally be expected to be covered with mycelium.

Cheyletus eruditus is a predatory, carnivorous mite. It does not live on farinaceous materials and is, therefore, not a direct pest of grain : it lives almost entirely on other mites. *Tyroglyphus*, being slow moving, is its chief prey, probably because *Glycyphagus* is protected by its long hairs and rapid movements. Relatively few

Cheyletus can quite quickly reduce a *Tyroglyphus* population to a very small size, though they will not usually completely extinguish it. The presence of *Cheyletus* is quite an important factor in controlling populations of *Tyroglyphus,* but the control is only effective under particular climatic conditions.

Solomon (1946) has shown that the relation between mixed populations of the predator *Cheyletus* and the prey *Tyroglyphus* depends on external conditions in the following way:

(1) *Cheyletus* is much more tolerant of fairly low humidities than is *Tyroglyphus.*

(2) *Cheyletus* requires a higher temperature for its rapid development than does *Tyroglyphus.*

(3) Under winter conditions in Britain, the low temperature and high humidity favour *Tyroglyphus*, so that its multiplication is very rapid and far outstrips the depredations of *Cheyletus.* Hence the infestation becomes primarily a *Tyroglyphus* population.

(4) In summer, higher temperatures and lower humidities favour *Cheyletus* development, and as there is abundant prey available to it remaining from the large population of *Tyroglyphus* which developed during the winter, multiplication is rapid. The predator soon reduces the prey population to a very low level and may almost extinguish it, so that a typical late summer infestation is composed chiefly of *Cheyletus.* This cycle may be repeated in the following years.

Gamasid mites are entirely carnivorous and never attack grain. Many of them attack other mites and they are also known to eat insect eggs and to attack living insects at all stages. Some of the Gamasids which are commonly found in grain are normally resident as vermin on the bodies of rats and mice. Not enough is known about these mites to say whether, on balance, their presence is to be regarded as desirable or otherwise, but, so long as there is a possibility of illness being caused to men or animals by the presence of mites (or other pests) in grain, it is probably best to regard all such pests as undesirable, even though some may appear to have advantages in controlling the numbers of others.

The life history of mites differs somewhat from that of the typical insect as described in an earlier article. Although the juvenile form, or larva, which emerges from the egg differs from the adult (being much simpler and having only six legs), it is not so different as is, for example, the larva of a moth or beetle from the adult form. Progress to adult size involves three or four moults. The larva is followed by three " nymphal " stages of which the second (called the deutonymph) is usually an active migratory form. In *Tyroglyphus*, however, and in other mites of the same group, the deutonymph is often omitted and the primary nymph moults to produce directly the third nymph (tritonymph). This in turn, in all mites, moults to produce an adult without the intervention of a pupa.

Both *Tyroglyphus* and *Glycyphagus* are capable of producing in their life cycle a special stage called the hypopus which takes the place of a deutonymph. The hypopus of *Tyroglyphus* has legs but moves little and is specially adapted to transport by attaching itself to insects.

The hypopus of *Glycyphagus* is very resistant to adverse conditions and is readily blown about in the wind but is itself immobile. The hypopus is thus a very important stage, because it enables the mite to be widely distributed and also enables it to survive unfavourable climatic conditions. It is not yet known for certain what conditions are necessary to cause the formation of the hypopal stage, which is relatively rare in *Tyroglyphus* but common in *Glycyphagus*.

Importance of Humidity

All mites are particularly sensitive to the humidity of the atmosphere in which they live. This is most true of the two Tyroglyphid mites mentioned (*Tyroglyphus* and *Glycyphagus*) as they have no special organs of respiration, all gas exchanges taking place through the skin. Although other mites have some respiratory organs, skin respiration probably plays quite an important part for them also. It is a consequence of relying on skin respiration, however, that the water loss cannot be controlled, and there is an ever-present danger that the mite will dry up and die if it is exposed to an atmosphere of excessively low humidity. For this reason, mite populations can only build up at high humidities.

The rate of damage to stored grain depends both on the humidity level in the dampest spots and on the proportion of the bulk which is moist enough to allow reasonably rapid mite development. It is also affected by other factors of which temperature is the most important. It is therefore not possible to give precise humidities which will permit various degrees of mite development, but the following may be a useful guide, at least for *Tyroglyphus farinae*. This mite cannot survive if the humidity is below 60 per cent., and between 60 and 70 per cent. populations either die out or else tend to remain static in numbers. Above 75 per cent. multiplication becomes rapid and the rate increases very greatly with increasing humidity.

This guide may be restated in terms of grain water content thus: Below 12 per cent. water content mites cannot live. At 14 per cent. they will usually multiply readily, but if mites are to build up to populations of serious dimensions from initially small infections, the grain water content must be in the region of 15 to 18 per cent., at least locally.

Undried English wheat harvested in a damp season is thus liable to very severe mite infestations if left undisturbed for more than a month or two, and the fact that this trouble does not always arise when these circumstances occur must be attributed to lack of an initial mite infestation. Dried English wheat, or any wheat imported from one of the great grain-producing countries is likely to remain free of

serious mite infestation unless parts of the bulk become damp owing to poor conditions of storage. A zone of dampness far too small to promote heating or appreciable mustiness may be sufficient to enable development of a very severe local mite infestation which can then spread into the bulk so far as water content permits.

It is very noticeable that the frequency and severity of mite infestations in stored grain in the British Isles increases towards the west and north of the islands. That is clearly related to the higher humidity in the west and the combination of high humidity and lower temperatures of the north. These factors not only affect the rate at which all mites multiply, but also increase the biological advantage which *Tyroglyphus* has over its predator *Cheyletus*.

Mites can be spread, particularly in hypopus form, in a large variety of ways which do not often influence insect distribution. Particularly, transport by mice and rats, and on the feet and coats of domestic and farm animals and on human clothes, are important means of distribution. Also they are known to blow about in the wind and to be carried to some extent by birds and, in hypopus form, by insects. The great mobility which these various vectors confer on mites result in their being nearly omnipresent in the damper parts of the country and although, as pointed out above, an infestation may fail to develop in suitably moist grain for a month or two because there is no initial infection, it is unusual for damp grain to remain uninfested for a longer period.

THE END

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The following list gives the full reference for each of the scientific papers and books referred to in the text; it is not by any means a complete bibliography of the subject. With very few exceptions the papers and books to which I have referred in the text are readily available in Britain and are those which I have thought readers likely to wish to consult for fuller details.

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